



# PV Tracker Lifetime Cost Assessment

Comparative Case Study

**ARRAY**  
TECHNOLOGIES

Array Technologies Inc

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# 1 Introduction

Array Technologies Inc. (“ARRAY”, “the Client”), one of the leading suppliers of PV tracking technologies, has appointed RINA Tech UK Limited (“RINA”) as an Independent Engineer, to perform a lifetime cost comparative assessment (the “Assessment”) of popular single-axis tracker architectures currently available in the solar PV market.

The Assessment has been structured in three phases, as follows:

- **Phase 1 - PV Tracker Lifetime Cost Methodology:** A methodology description to perform a “Tracker lifetime cost assessment” covering characteristics structured and features of current market standard single-axis trackers.
- **Phase 2 - Model based on the Methodology:** Implementation of a model based on the above methodology, to allow for a practical comparison between different single-axis trackers, aiming to help customers objectively make buying decisions.
- **Phase 3 – Comparative Case Study:** A strictly-independent comparative analysis (the ‘Case Study’) for a specific PV plant (‘the Project’) using ARRAY tracking system with the same PV plant equipped with an equivalent configuration with other market-standard PV single-axis tracker architecture.

This report addresses the third phase of the Assessment, the Case Study.

The Methodology (Phase 1) is fully described in the accompanying report; “PV Tracker Lifetime Cost Assessment Methodology\_v1”, issued by RINA on 1<sup>st</sup> June 2020 [1], which should be considered in conjunction with the results presented within this case study.

The model developed by RINA based on the Methodology (Phase 2); “PVTrax – PV Tracker Lifetime Cost Assessment Model\_v01”, issued by RINA on 3<sup>rd</sup> June 2020 [2], has been used to perform the simulations underpinning this comparative Case Study. The model, named PVTrax<sup>1</sup>, is expected to be publicly available on RINA’s website from June 2020.

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1 PVTrax is a publicly available modelling solution developed by RINA to provide project owners, developers and funders with detailed insights on expected lifetime operational costs for single-axis tracking solutions currently available within the market. It is a model based on the above mentioned PV Tracker Lifetime Cost Methodology. While RINA has been commissioned to produce PVTrax by ARRAY, as part of the Assessment (phase 2), we have developed the tool from the perspective of an independent technical advisor, ensuring that we are comfortable that assumptions feeding into the model are reasonably representative and objective.

PVTrax has been designed to allow for a quick and practical lifetime cost comparison between two single-axis tracking technologies assuming the same PV plant design and project common assumptions, with the exception of the specific inputs related to each tracking technology.

The tool allows modelling for most of the single-axis tracking technologies and major components’ variants currently available in the market.

PVTrax models and estimates lifetime failures profiles of the key components of a PV tracking technology and provides users with lifetime cost projections (fixed and variable cost), LCOE (Levelised Cost Of Energy), NPV (net present value) and net lifetime generation for two variations of the same PV plant design using the two single-axis tracking technologies under comparison. PVTrax enables users to make informed decisions when selecting tracking system solutions and vendors at the developing and bidding stages of the project.

The results described in this report have been established using the open source [PVTrax](#) software which is expected to be publicly available at RINA’s website (on request) from June 2020.

Photovoltaic (PV) power plant equipment is typically selected based almost exclusively on upfront cost (capital expenditure or CAPEX). However, the cost of ownership for each component of a PV plant includes not only the cost of supply and installation (CAPEX), but also the associated operation and maintenance costs (operational expenditure or OPEX) of the component over the lifetime of the PV plant.

Although developers often account for operational costs through either Maintenance Reserve Accounts (MRA) or other OPEX assumptions within their Financial Model, OPEX are not generally well-assessed when selecting the technology of the PV plant during the RfP (request for proposal) or tendering process. Instead, EPC bidding processes for PV power plants are typically driven purely by CAPEX costs. Conducting a comprehensive lifetime cost assessment can provide asset owners with valuable insights into component selection which would allow owners to improve the profitability and minimise operational risks of a project, particularly in the context of contractor warranty periods, which generally extend for only two years following the completion of construction.

## 1.1 Comparative Case Study

The aim of the Case Study is to compare the level of suitability of two PV tracking technologies (ARRAY's centralised single-axis tracker vs a single-axis tracker with distributed architecture available in the market) through a lifetime cost analysis. RINA has analysed lifetime cost through two main metrics; Levelised Cost Of Energy (LCOE) and net present value (NPV). For further detail on these metrics see Appendix B.

The comparative case study has been performed for a specific sample project location selected to ensure a fair comparison between technologies. The assessment estimates the lifetime OPEX of the two tracking technologies under comparison and the impact of the trackers' failures on the lifetime performance of the PV plant. Fundamental financial parameters have been considered in the model (i.e. discount rate, inflation and price of electricity). It is noted that RINA has been instructed to assume that both tracking technologies have the same CAPEX. We suggest this assumption is confirmed by developers through competitive tender, and if the reader does want to vary CAPEX figures this can be easily achieved through PVTrax. The PV tracker lifetime cost Methodology and its associated model developed by RINA (PVTrax) have been designed to provide comparative guidance on the cost competitiveness of different tracker solutions for a PV project, but do not constitute investment advice, and should not substitute for detailed and project specific financial modelling based on technical due diligence and competitive tendering as well as other project-specific variables.

This analysis specifically compares Tracker A, the DuraTrack HZ v3 PV centralised tracker produced by ARRAY (up to 32 linked rows with articulated and disconnecting rotational drivelines) to Tracker B, an alternative single-axis tracking technology which has material market penetration for distributed self-powered single row trackers. Further to the base-case project scenario, a selection of project design sensitives have been modelled as part of this assessment in order to provide further insights as to the performance of the Tracker A system when compared with the Tracker B single-axis alternative.

The Case Study is performed for a hypothetical 100 MWp PV plant located somewhere in California, US. While the conclusions derived from this assessment could be interpreted as applicable to sites with similar characteristics, it is noted that PV projects have a number of unique features and constraints (e.g. localised irradiance conditions, project design choices such as

ground cover ratio, selected modules and inverter technologies, electrical configuration, tracking algorithms supported, labour costs, delivery costs, tracker component costs, cost of electricity, inflation, discount rate, project size, etc.) hence a project specific assessment is recommended in order to determine which tracking technology is more favourable. Such an analysis can be performed by the reader through PVTrax.

RINA notes that while this report was commissioned by the Client, it has been performed by RINA in the role of an Independent Engineer, and hence contains our independent opinions on Tracker A in relation to Tracker B. This report is intended to be considered in its entirety and specific statements quoted in isolation have not been endorsed for marketing purposes.

## 1.2 Report Structure

This comparative Case Study is structured as follows:

- Section 1: Introduction
- Section 2: Technical overview of the tracking technologies considered
  - Tracker configurations
  - Design and system flexibility
- Section 3: Reliability and maintenance requirements
  - PV tracker components
  - Component failure and maintenance modelling
- Section 4: Case Study inputs and assumptions
  - Project specifications for the Case Study
  - Energy yield assessment
  - Assumptions
  - Inputs to the model
  - System components and quantities
  - Lifetime cost and losses assessment
- Section 5: Case Study results and discussions
  - Tracker lifetime cost, LCOE and NPV
  - Sensitivity scenarios run and their relative impact on results
- Section 6: Conclusions
- Section 7: Referenced documents

## 2 Technical overview

RINA has undertaken an evaluation of the critical technical components comprising Tracker A (the ARRAY DuraTrack HZ v3 PV tracking system) and Tracker B (alternative distributed single-axis tracking system). This assessment was carried out to verify the technical suitability of the proposed solutions for the case study project, in addition to evaluating how Tracker A compares to Tracker B.

Outlined below is an overview of single-axis tracking technologies and the associated merits and limitations of Tracker A when compared to other Tracker B type technologies.

### 2.1 Tracker system configurations

#### 2.1.1 Overview of technical solutions considered

The energy generated by a solar panel is a function of the amount of light to which each module is exposed. Greater irradiation will be experienced by a module which faces the sun directly. As the sun moves throughout the day, energy generation can be improved by mounting modules on a structure which tracks the sun. Throughout any day the sun moves in two axes relative to the horizon (up and down and east to west). Hence the highest performing tracking technology would move in two axes. However, the industry has found that single axis trackers typically offer a better balance of cost, complexity and generation in comparison to dual-axis trackers.

There are several common implementations of single-axis trackers. This review is focused on horizontal single axis tracking systems (HSATs), which are currently the most widely deployed technology. This section intends to provide a high-level description of the key aspects of the two common PV HSAT technologies (centralised and distributed architectures) currently available in the market in order to support the understanding of the comparative study.

The most fundamental difference in mechanical architecture between single-axis trackers is related to whether the rows are linked to a common transmission system (centralised architecture) or operated independently (distributed architecture) as outlined in Figure 1.

The technical distinction between the solutions is discussed in further detail below, with specific reference to the Tracker A solution where applicable.

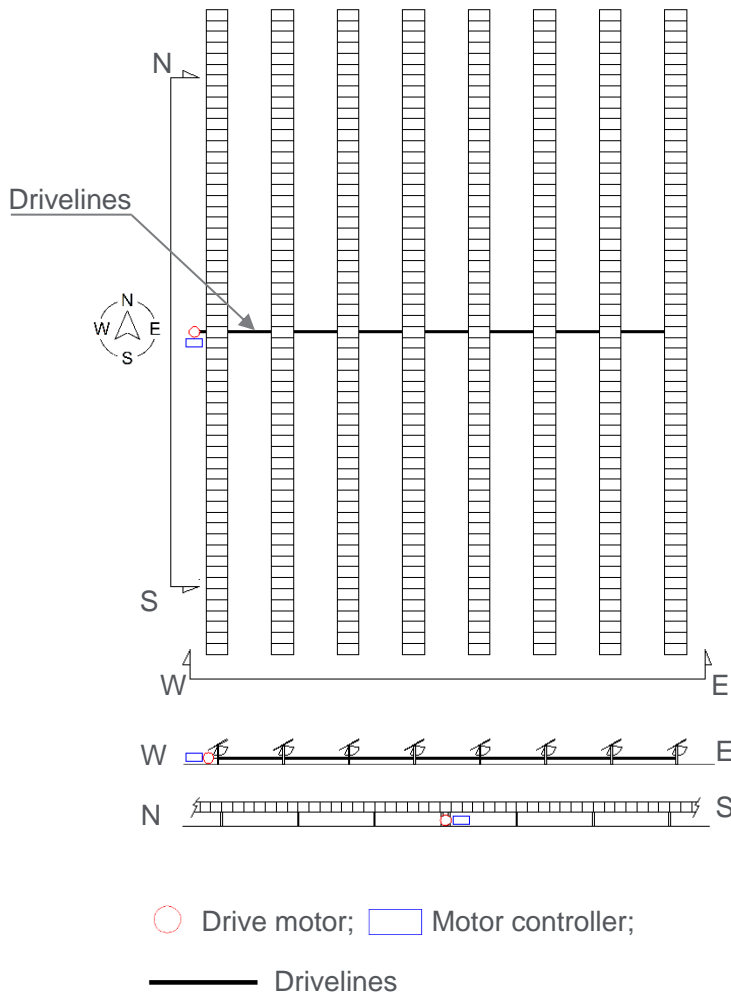
#### **Multi-row tracking system (Tracker A, Centralised Architecture)**

Centralised trackers are the traditional architecture of HSAT, where a few rows of modules (generally from 15 to 30 rows, with the Tracker A system capable of up to 32 rows) are linked to a single (or in some cases two or more) motors. These motors are used to drive all linked rows (refer to architecture shown in Figure 1a). Each row consists of a metal tube (torque tube) arranged in the north-south direction and supported by equally spaced columns driven into the ground. The support points consist of a bearing system that allows the tube to rotate in the east-west direction. PV modules are clamped onto the upper side of the torque tube, allowing them to follow the sun. Tracker A is a centralised single-axis tracker system with a single motor located in the first row.

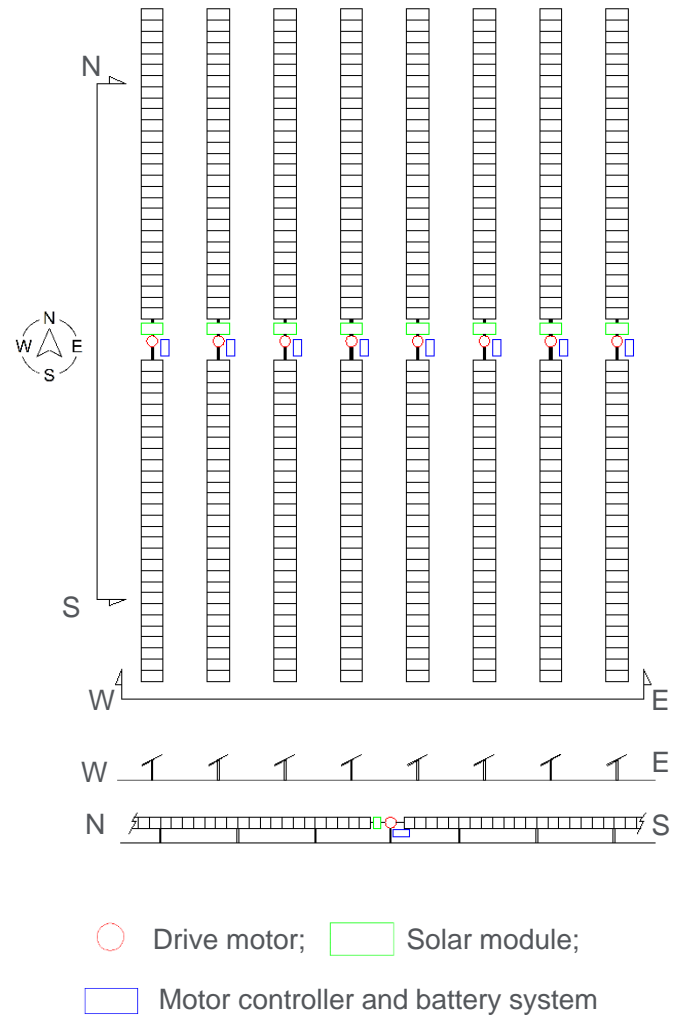
Transmission systems in most centralised architectures are based on push-pull drivelines, with few manufactures featuring rotating drivelines. This assessment is focused on the rotating gear type drivelines employed by Tracker A. For the rotating driveline solution, the motor rotates the driveline,

which in turn, by means of gearboxes (worm gears and gear racks), rotates the torque tubes (and the solar modules mounted on it) in the east-west direction.

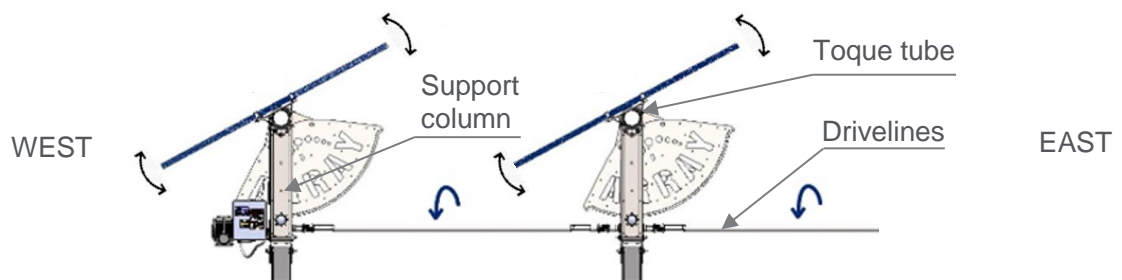
**Figure 1a: Multi-row tracking system (Tracker A)**



**Figure 1b: Single-row tracking system (Tracker B)**



**Figure 2: Tracker A – Disconnecting articulated-rotating drivelines**



Tracker A's rotating drivelines are articulated, thus allowing for greater flexibility to accommodate the tracker to complex terrain than traditional push-pull centralised architectures which, due to the use of solid drive strut to link the rows, have a very limited tolerance to operate over high ground between rows. Additionally, the Tracker A solution allows for quick disconnection of the drivelines to facilitate the movement of machinery between rows when performing operation and maintenance (O&M) works such as cleaning or mowing. Disconnecting drivelines provides Tracker A with similar flexibility to non-linked architectures (Tracker B) with regards to O&M activities.

The fact that Tracker A features articulated rotating drivelines with disconnecting capabilities, introduces a great improvement with respect to traditional centralised architectures, and makes it suitable for most of the common land topographies typically used in utility PV ground mount plants with no need of earthworks (e.g. grading).

### Single-row tracking system (Tracker B, Distributed Architecture)

For the distributed architecture, rows of modules are independent, which means that each row has its own motor, transmission system (gearbox), controller, and power supply system (batteries or equivalent). Such an architecture is shown in Figure 1b, which would be repeated across the solar field.

Single-row tracking systems effectively address the design limitations of multi-row architecture (unlimited tolerance in the east-west direction, no drivelines obstructing machinery when performing operation and maintenance works) at the expense of a larger number of electromechanical components (roughly 15-30 times as many motors, controller and autonomous power supply systems, as these are included on a per row basis). Drive motors in distributed architectures are generally either self-powered (using a dedicated solar module and battery) or parasitically powered (connected directly to the PV array or fed from an external power supply). Slewing<sup>2</sup> drives are the most common technology used for the transmission in single-row trackers. However, some systems feature linear actuators or equivalent instead of slewing drives.

Tracker B is a self-powered distributed system (single-row) with a drive motor, a controller, a battery, a battery charger and a solar module per tracker (i.e. per row).

## 2.1.2 Fundamental components

As introduced above, the centralised and distributed trackers both require a suite of key components in order to operate effectively. A general overview of key components of a single-axis tracker which could be installed on a project are outlined in Table 1 below. Discussion on the specific design assumptions and component lifetime costs is introduced in Section 3.

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2 The slewing drive is a gearbox, typically used in distribute architectures of single-axis trackers, installed in the centre of each torque tube and in charge of transmitting the rotating torque. It functions with a standard worm gear technology, with the worm on the horizontal shaft (operated by the drive motor) acting as the driver of the gear.

**Table 1: Summary of the key parts of a single-axis tracker**

Key parts	Centralised System (Tracker A)	Distributed System (Tracker B)
Support columns	<p>The posts on which the tracker is mounted. Assumed that will last for the lifetime of the PV plant (not considered in the Methodology for the tracker OPEX estimation)</p> <p>For the purpose of quantification of other parts (e.g. bearing, dampers, and transmission units) this assessment has assumed that both tracking solutions will have the same number of support columns per row (11) and the same number of modules per row (90) to ensure a like-for-like comparison.</p>	
Torque tube and bearings	<p>A torque tube is the rotating beam on which the PV modules are mounted. Torque tubes are connected to support columns via a bearing system required for the east-west rotation.</p> <p>Torque tubes are assumed to last for the lifetime of the PV plant. Only bearings are considered in the Methodology for the tracker OPEX estimation.</p>	
Transmission system	<p>The transmission in multi-row systems is generally based on push-pull or rotating drivelines (Tracker A) set in the east-west direction. It includes all of the parts within the driveline system responsible for rotating the linked torque tubes of the multi-row tracker, including the gearboxes and gear racks for rotating drivelines, or the drive gearbox and connecting rods for push-pull drivelines.</p>	<p>In single-row systems, each row is equipped with a dedicated transmission system responsible for rotating a single torque tube. Slewing drive (Tracker B) mechanisms are more common, however, linear actuators are also used by some single-row manufacturers.</p>
Drive motor	<p>Motors power east-west rotation of multiple rows (Tracker A, centralised architecture) or a single row (Tracker B, decentralised architecture) by acting on the transmission system. Although generally there is one drive motor per tracker, some manufacturers of centralised and decentralised architectures use two drive motors per tracker. Most of the single-axis trackers systems use DC brushless (Tracker B), AC brushless (Tracker A) or DC brushed (less common) electric motors. Brushless motors are more reliable featuring longer lifespan than brushed motors.</p>	
Tracker controller panel	<p>Trackers are equipped with all of the electronics (controller, power supply, GPS, communication cards, etc.) required to perform the required tracking algorithm. Apart from the motor controller present at each tracker, a master controller unit responsible of monitoring and controlling a certain number of motor controllers is generally used by most single-axis tracker manufacturers in both centralised and decentralised architectures.</p>	
Power supply	<p>Commonly, centralised systems are parasitically powered (Tracker A) via a wired cable to the closest auxiliary services LV switchboard.</p>	<p>Distributed systems may be either self-powered or parasitically powered. Tracker B is self-powered with a</p>

Key parts	Centralised System (Tracker A)	Distributed System (Tracker B)
		lithium-ion battery powered by a solar module.
Communications	Communications may be wired or wireless regardless of the type of the single-axis tracker architecture. However, wireless systems are typically used by single-row systems. Tracker A uses wired communications while Tracker B is assumed to use wireless communications.	
Active safety stowing system	<p>An active safety stowing mechanism is generally required for most architectures, to move modules to a lower loaded configuration in high wind or high snow situations. Stow angle varies with tracker manufacturer. Traditionally, wind stow angles were 0 degrees or near to horizontal, however, some manufacturers are currently using angles around 30 degrees as the optimum to prevent fluttering issues. Snow angles go from 45 degrees to the maximum supported. These systems include the secured power, additional sensors, local electronics and control logic required (e.g. anemometers, data logger, power supply and controllers) to ensure that the tracker can be set to a safe position even under a power outage. Some manufacturers do also use weather forecasting data (where applicable) to stow the system in advance (e.g. a day before) to reduce the risk of structural damage.</p> <p>In contrast to active stowing, passive stowing mechanisms do not require the installation or maintenance of the above mentioned active components to preserve the integrity of a tracker.</p> <p>PVTrax does not consider damage from malfunctions associated with passive or active stowing mechanisms, but less reliable or malfunctioning systems could introduce structural damaged into the system which would incur additional operational costs.</p>	
	Tracker A features a proprietary passive safety stowing mechanism.	Tracker B is based on an active safety stowing system.

## 2.2 Design and system flexibility

Within the scenarios modelled, both horizontal single-axis tracking solutions (HSAT<sup>3</sup>) have assumed the same form factor in terms of a single clamp per module and rows with one module in portrait orientation (1P).

Items raised below outline the available functionality of Tracker A when compared with the Tracker B solution used in our case study project and associated modelled scenarios.

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<sup>3</sup> Mounting structure (torque tubes) installed along north-south direction in order to enable the modules to track along the east-west direction.

## 2.2.1 Site setting

Subject to the project boundaries and topography, the tracking system chosen can result in limitations to the design and layout of the PV project.

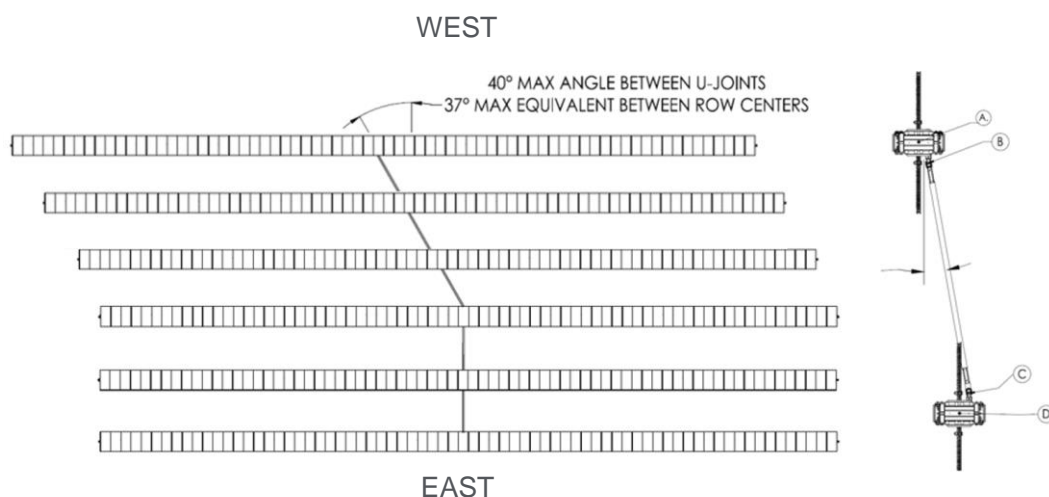
Generally single row tracking systems offer the greatest level of flexibility. Each row has its own motor and transmission system and, as such, each row can be offset to follow the shape of the project boundary (if required) and have more flexibility to terrain in the east-west direction. In practice, tolerance is limited as the more exposed to the wind the rows are (either due to the row's offsets or the unevenness of the land in the east-west direction) the higher the cost of the structure.

As multi-row trackers utilise a central driveline, this has historically limited the deployment to a fixed block type layout where all rows are aligned, thus resulting in reduced land use when instances of irregular site boundary do not permit a full block to fit on site.

The Tracker A solution has addressed this shortcoming through the use of an articulated rotating drive line. By employing an articulated rotating driveline (flexible up to 40 degrees compound angle in all directions), Tracker A is able to use a range of offset rows in order to work within the land area available for PV deployment (see Figure 3). The use of angled drivelines throughout a block can decrease the number of rows that can be driven by a single drive motor (from 100% of rows available for angles within 0-15 degrees down to about 70% for maximum driveline angle of 40 degrees, for Tracker A).

While this does not grant the same theoretical level of flexibility as a single row solution, terrain tolerance of Tracker A is within the practical tolerances commonly used in projects using single-axis systems and does represent an advantage in comparison with many other classical centralised trackers.

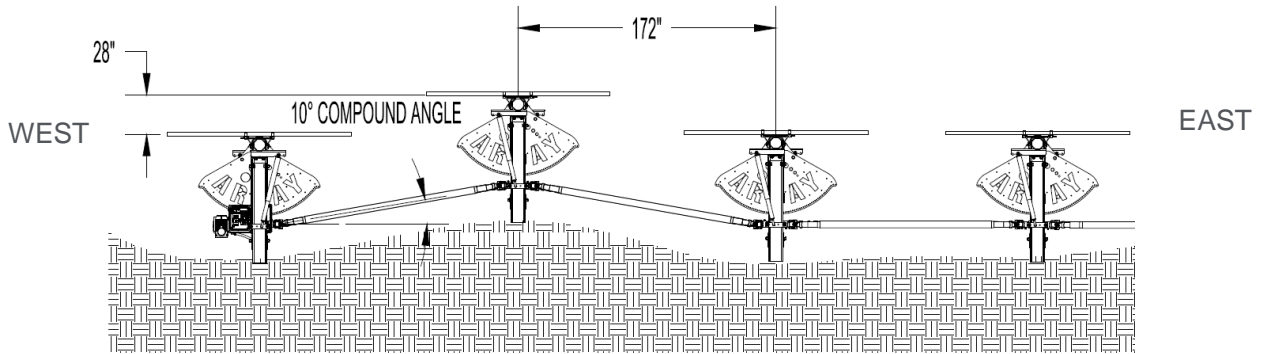
**Figure 3: Tracker A – Driveline flexibility to shift rows (north-south direction)**



A, D – Drive motor (row centre); B, C – U-joints (articulated drivelines)

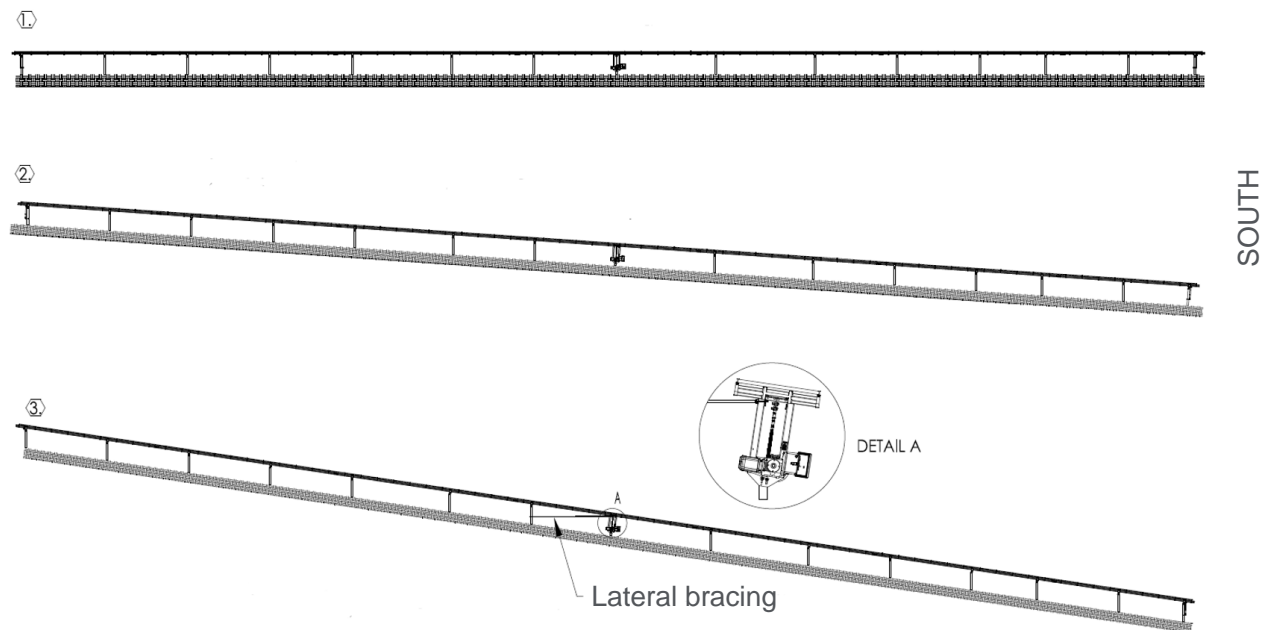
While traditional centralised systems present issues on sites with variable height of land between rows (in the east-west direction) due to the limited tolerance of their solid drivelines, the articulated and rotating drivelines of Tracker A almost eliminate this limitation thanks to its flexibility of up to 40 degrees driveline change between rows (see Figure 4)

**Figure 4: Tracker A – Driveline flexibility to terrain topography (east-west direction)**



When considering the up/down topography of a site, along the tracker’s rows (torque tubes) Tracker A offers good flexibility when compared with most of other single-axis tracker manufacturers. Typically the torque tube would need to be installed along a horizontal plane, thus requiring pile lengths to be adjusted across the site. Tracker A provides a north-south tolerance between 0 to 8.5 degrees as standard, which is in line with the maximum site slope supported by Tracker B (15% or 8 degrees). Tracker A supports a maximum site slope of up to 15 degrees available as an added optional solution (see Figure 5).

**Figure 5: Tracker A – Terrain tolerance along the torque tube<sup>4</sup>**



4 This example assumes site on the northern hemisphere.

Overall, we consider that the terrain tolerance provided by the articulated rotating drivelines of Tracker A (having a driveline flexibility of 40 degrees in all directions), together with the considerable site slope flexibility in the north/south direction (up to 15 degrees) means that, over a typical project terrain, Tracker A can be deployed effectively.

Although the decentralised mechanical architecture of Tracker B offers slightly better design flexibility with regards to sites with highly irregular boundaries and/or greatly uneven ground in the east-west direction, for a typical site there is limited difference in flexibility between Trackers A and B.

### 2.2.2 Operational design considerations

As with any solution that requires a driveline to be installed through the PV arrays, there are additional complexities which need to be accounted for when considering the long-term operation of the technology.

The cost of cleaning and mowing operational works related to the PV plant may be affected differently depending on the individualities of each PV tracker:

- **Cleaning** costs vary depending on the cleaning frequency required for the project, with potential impact due to the architectural features of the tracker technology (e.g. presence of drivelines, gaps between modules). Owners typically include the cleaning cost in non-tracker OPEX (PV plant OPEX), with the obligation performed by the O&M contractor.
- **Mowing** costs vary depending on the mowing frequency agreed for the project and potential impact due to the architectural features of the tracker technology (e.g. presence of drivelines, inter-row spacing). Mowing cost is typically accounted as part of the PV plant OPEX, as is the case with cleaning.

The main distinction between the single and multi-row tracking solution is the central rotational driveline used for multi-row systems. This results in additional complexities for some maintenance tasks, such as tractor based cleaning and mowing. For single row trackers the process is less complex and whole rows can be cleaned and inter row spacing mowed. However, with a driveline, tractors are required to complete each row up to the central driveline before reversing back along the row and approaching from the other end. This increases the time (and therefore cost) required for standard maintenance activities and potentially increase of tracker unavailability (e.g. longer time with the tracker on cleaning position) compared to distributed technologies. It should be noted that some developers do use above-ground cable trays, whether in single row or multi-row tracking systems, in an effort to reduce costs. RINA does not recommend such an approach for single-row systems (where possible), as it creates O&M challenges described in this paragraph, but if above ground cable trays are used in a decentralised solution similar mowing and cleaning challenges will be experienced as with a driveline.

Tracker A utilises a proprietary detachable driveline solution which enables site maintenance operatives to easily detach drivelines before commencing these works and attach them once the works are completed. In practice, once the drivelines have been detached, a site can be maintained under the same conditions as a single row or fixed tilt mounting system. The disconnection and connection of the rotating U-joints is simple hence likelihood of a fault as a result of disconnection and reconnection is low.

RINA considers that the disconnecting driveline functionality of the Tracker A system places it above more standard multi-row systems. However, the cost savings of implementing this type of maintenance programme would need to be assessed based on the project location. Subject to labour costs within a given market, the time efficiencies realised for mowing and cleaning with the detachable solution may not be material and should be considered in terms of the additional wear and tear that this may place on the tracking system (if any).

Feasibility of alternative cleaning methods to traditional tractor based ones, such as robot cleaning solutions, depends on the number and dimension of the gaps between modules along the tracker's rows – more complex shapes are harder to clean. In most decentralised architectures there is a significant gap (of about a metre) in the centre of the row where the drive motor, motor controller panel and self-powered solar modules are installed. In Tracker A, all modules in a row are installed next to each other with the standard clamp gap of within 1.5-2cm between them (the motor and motor controller panel are located underneath the torque tube). This eases robotic cleaning challenges when comparing Tracker A to B.

For the Case Study, tracker based mowing and cleaning have been assumed, since these are the most common methods used. Although mowing and cleaning costs are typically included in PV plant OPEX, the extra cleaning and mowing costs (deviation) incurred by Tracker A due the additional labour work of disconnecting and reconnecting the drivelines have been accounted for in PV tracker lifetime cost (O&M contractors are expected to offer higher prices to manage such complications)

Further discussion on maintenance expectations and assumptions is provided in Section 3.3.

### 2.2.3 Procurement and installation

This assessment makes no material distinction between the procurement and installation works which would be required for Tracker A or Tracker B. This assumption would need to be validated through competitive tender on a project specific basis. We note that PVTrax can be used to capture project specific considerations and could be used to account for costs associated with technical or logistical mitigations required by a given vendor for a specific project location.

In the scenarios modelled, it is assumed that both tracking manufacturers have suitable infrastructure to supply the case study project.

### 3 Reliability and Maintenance

RINA has undertaken a review of the anticipated electromechanical adequacy of the solutions considered as part of this assessment.

#### 3.1 PV Tracker Components

RINA’s PV tracker lifetime cost Methodology Report [1] identifies and lists the fundamental components (named expenditure units or EUs) that should be assessed when estimating the fixed OPEX (preventive maintenance) and variable OPEX (corrective maintenance) associated with the most common PV single-axis tracking architectures on the market.

Table 2 summarises the expenditure units that applies to the two tracking technologies of this comparative Case Study.

**Table 2: Key parts of the PV Tracking Technologies responsible for the PV Tracker OPEX**

Tracker part (EU)	Tracker A	Tracker B
Drive motor	AC brushless motor	DC brushless motor
Transmission unit <sup>5</sup>	Worm gear Gear rack Rotating drivelines joints (Centralised architecture)	Slew drive (Distributed architecture)
Bearing (one per support column)	Yes	Yes
Harmonic damper (two per row)	Yes	Yes
Motor controller (one per tracker)	Yes (1 every 30 rows)	Yes (1 per row)
Master controller	Yes (1 every 180 rows = 6 trackers)	Yes (1 every 100 rows or trackers)
Power supply	No (Parasitically powered) 203 kWh/year/tracker	Yes (Self-powered) Battery (1 per row) Battery charger (1 per row) Solar module (1 per row)

<sup>5</sup> The model assumes one “transmission unit” per row. For centralised architectures with rotating gears (Tracker A) each transmission unit includes a worm gear, a rack gear and two drivelines joints. For distributed systems it includes the slew drive (Tracker B) or linear actuator (other manufacturers). The drive gear is considered included as part of the drive motor (when estimating failure rates and replacement costs) for all architectures.

Tracker part (EU)	Tracker A	Tracker B
Active safety stowing system	No	Yes <sup>6</sup> Anemometers Data loggers Stowing controller Battery Battery charger Solar module
Mowing	Yes (Disconnecting drivelines)	Yes (No drivelines)
Cleaning	Yes (Disconnecting drivelines)	Yes (No drivelines)

As demonstrated above, distributed systems (Tracker B) require a greater number of components (which may require preventive maintenance, corrective maintenance or both) when compared with centralised systems. This is principally because each row is equipped with a drive motor and associated equipment, whereas a centralised system has only a single motor per tracker, i.e. per a cluster of 30 rows. No power supply components are required in Tracker A since it is parasitically powered from an external auxiliary power supply. The above table only intends to illustrate the architectural differences between Tracker A and B with regards to OPEX estimation. Quantities of PV tracker key components for the specific Project of the Case Study are provided in Section 4.

Further details on this topic is available in Appendix C.2 and RINA's PV tracker lifetime cost Methodology Report [1].

## 3.2 System Reliability

The number of components of each tracking technology and the granularity of the trackers (number of modules or DC capacity driven by each motor) is directly related to system reliability.

### 3.2.1 Quantities

In terms of the number of plant components, we note that the single row Tracker B system will have more points of failure due to the greater number of key electromechanical components required for operation of each row. For the single-row solution, each row will have its own drive motor, a motor controller, a battery, a battery charger and a solar module, while the Tracker A utilises a single motor and controller for up to 32 rows.

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<sup>6</sup> Assuming a safety stowing kit every 25 MWp (4 kits for the 100 MWp PV plant Case Study). Each kit is expected to include (as minimum) 1 x anemometer, 1 x data logger, 1 x battery, 1 x battery charger, 1 x solar module. Minimum figures for the stowing kit have been assumed in the model for the Case Study. A single stowing controller has been considered for the entire site.

### 3.2.2 Granularity

In contrast, Tracker A relies on a centralised architecture, such that a single failure of a critical component such as a motor or a motor controller would affect a larger number of rows of modules (i.e. 30 rows) than for Tracker B (i.e. a single row).

In the Case Study discussed in Section 4, components responsible of the movement of the tracker have been quantified for each tracking technology and lifetime failures have been estimated and their related costs and tracker unavailability estimated along the lifetime of the tracker. Results and commentary on how Tracker A compares with Tracker B is also included in Section 4.

### 3.2.3 Safety stowing

#### Decentralised architecture

One area where significant additional component complexity arises is in relation to the safety stowing system. In order to prevent structural failure, torsion damage to the mounting structure and potential damage to associated equipment, e.g. PV module micro-cracks and module or wiring damage due to torsion and vibrations within tracking system, a safety stowing system is used by most of the tracking technology providers. This stowing system is activated in the event wind speeds increase over a certain design threshold and pose a risk to the tracker or its modules.

Tracker B, like a wide variety of other PV trackers on the market, is designed under the assumption that in the event of high wind speeds the rows of the PV tracker will be set to a specific safe angle to ensure the integrity of the PV tracker (active safety stowing mechanism). The safe angle varies with the manufacturer and technology. Typically, trackers with active stowing mechanisms stow at horizontal position (angle near 0 degrees) although it may vary with tracker manufacturer and project design assumptions.

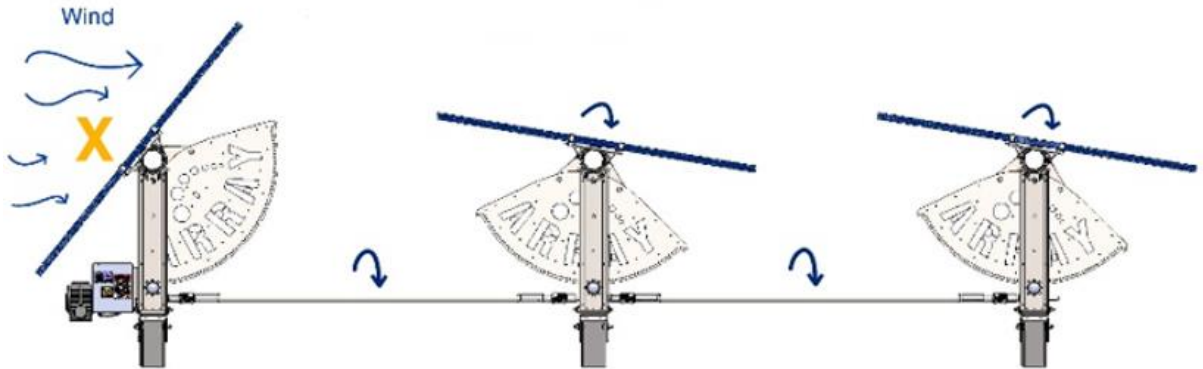
Local weather stations, including anemometers with associated data logging and control electronics, are typically installed at PV trackers with active safety stowing mechanisms in order to monitor the wind conditions. Some trackers manufactures do use forecasting data together with the local wind measurements in order to stow the system in advance (e.g. the day before) as a measure to mitigate tracker damage risks. Tracker B has been assumed not to use forecasting, but the OPEX associated with maintenance of all components comprising the active safety stowing system is captured in our modelling.

#### Centralised architecture

The Tracker A approach to addressing risks associated with wind speed is to use a proprietary passive mechanical stowing mechanism with a torsion limiter installed on the central supporting columns for each row. One advantage of this mechanical stow system is that it does not require a power source, nor additional electromechanical components or wind sensors.

This mechanical passive stowing system enables each row affected by high wind or an obstruction such as snow to be independently held in position to avoid risk of damage. For a wind/obstruction event, external rows are typically the first to be impacted. As such, the passive stowing system of Tracker A will allow these rows to be rotated to the near vertical position, with the load being shared across the supporting columns foundations. In an obstruction event, the row will be held in position. The remaining rows will still be able to operate independently of the row affected by the wind/obstruction event and hence still generate optimal revenues. The functionality of the system is demonstrated in Figure 6 and Figure 7, produced by ARRAY.

**Figure 6: ARRAY passive wind mitigation stowing system**



**Figure 7: ARRAY passive obstruction mitigation stowing system**

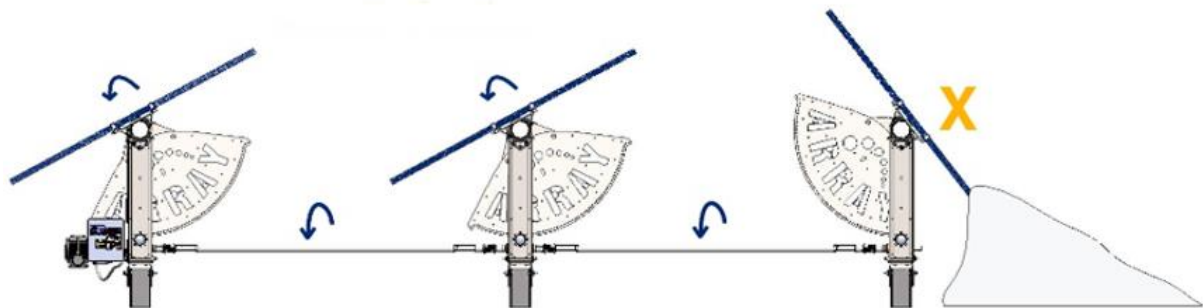


Figure 6 shows how the first row of the tracker is in passive stow position while the others are tracking normally since there is no high wind facing on them. Something similar is shown in Figure 7 where only the last row is obstructed with snow while the rest is not rotating normally.

Since the passive stowing system requires neither active components (electronics, sensors, controller and secured power supply), nor communications between the motor controllers and the master controller, the Tracker A solution is considered robust. The Case Study considers the reduced OPEX associated with the reduced number of components when compared to an active stowing system. We note that although PV plant underperformance due to tracker failures has been estimated for both tracking systems, energy losses due to potential active or passive stowing have not been considered in the Case Study.

### 3.3 Component failure and maintenance

Apart from PV tracker granularity and quantities of components, system reliability and durability is strongly dependent on type of technology of the fundamental components of the PV tracker. PV tracker OPEX will be driven by the required preventive maintenance of the components of the system together with the corrective maintenance expected along the lifetime of the PV plant in order to replace faulty components. Preventive maintenance assumed for each tracker architecture and details of the component failure modelling used to estimate corrective maintenance requirements are discussed in the following sections.

### 3.3.1 Preventive and corrective maintenance requirements

PV tracker OPEX includes fixed (preventive) and variable (corrective) expenditures expected to ensure the correct operation of the tracking systems during the lifetime time of the PV plant.

RINA has assessed the technologies of the components of both Tracker A and Tracker B, and identified the required preventive activities based on our experience, information publicly available, and manufacturers' information and recommendations.

RINA's PV tracker lifetime cost Methodology assumes that standard preventive checks which are common to all tracking technologies, such as torque verification or corrosion and defective parts checks, are included within the scope of the standard O&M contractor and therefore included in "non-Tracker OPEX". Only those preventive maintenance tasks that are specific to the tracking technology are modelled as part of the Case Study.

In Table 3 below, we have identified which specific components have been assumed to be covered under the PV trackers' preventative maintenance schedule for the Case Study PV project.

**Table 3: Preventive maintenance schedule assumed for the case study PV project**

Unit type	Tracker A	Tracker B
Drive motors (including the drive gear) -AC brushless – Tracker A -DC brushless – Tracker B	Yes, ARRAY recommends regular maintenance - Frequency: yearly - Quantity: 100% of the drive motors. - Labour time: 0.25 man-hours per unit - Consumables: \$1.00 per unit	No, typically operated to failure
Transmission units -Worm gear, gear rack and joints (Tracker A) -Slew drive (Tracker B)	According to ARRAY it is a sealed unit (with components immersed in synthetic lubricant) and lifetime tested in a dust chamber. We note that since the gear racks are exposed to dust, maintenance may be required in dusty climates. However ARRAY considers no maintenance is required.	No, as sealed system
Bearings	No, typically operated to failure	No, typically operated to failure
Harmonic dampers	No, typically operated to failure	No, typically operated to failure
Motor controllers	No, typically operated to failure	No, typically operated to failure
Master controllers	No, typically operated to failure	No, typically operated to failure

Unit type	Tracker A	Tracker B
Self-powered supply components (Tracker B) -Battery -Battery charger -Solar module	N/A as tracker does not have these components	No, typically operated to failure
Active safety stowing equipment (Tracker B) -Anemometers -Data loggers -Stowing controller -Battery -Battery charger -Solar module		Yes Anemometers only - Frequency: Every 2 years - Calibration cost: \$125.00 (including labour and shipping)
Active safety stowing functional checks		Yes - Frequency: yearly - Scope: Check the correct operation of the system. - Labour time: 5 days, 2 people to test 100 MWp - Consumables: \$0.00
Mowing <sup>7</sup> -Disconnecting drivelines (Tracker A) -No drivelines (Tracker B)	Yes (only extra mowing cost compared to Tracker B, disconnecting and reconnecting drivelines)	No (only considered when evaluating the use of cable trays in the sensitivity analysis section)
Cleaning tractor based <sup>7</sup> -Disconnecting drivelines (Tracker A) -No drivelines (Tracker B)	Yes (as above)	No (as above)

### 3.3.2 Failure rate modelling approach

Both tracking architectures are comprised of electro mechanical components which are susceptible to failure. PVTrax models the lifetime failure profile of each PV tracker as the combination of a constant annual failure rate (random failure rate) together with a normal (Gaussian) distribution

<sup>7</sup> Mowing and cleaning costs are not Tracker's OPEX but PV plant OPEX. However, mowing and/or cleaning costs may be impacted depending on the tracker architecture (e.g. presence of drivelines). As described in RINA's PV tracker lifetime cost Methodology [1], only the extra mowing and cleaning cost (difference cost) referred to the cheapest case will be accounted as tracker OPEX. Assumed mowing and cleaning prices are listed in Section 4. "No drivelines" systems (Tracker B) have the cheapest mowing and cleaning costs (tractor based cleaning assumed), therefore, mowing and cleaning extra costs only apply to Tracker A.

which represents the component life expectancy in line with their expected wear-out. The tool models the failure profiles of the components based on component technology (e.g. electronics, brushed motors) rather than equipment of specific manufacturers. This has been performed to ensure a like for like comparison, under the assumption that the manufacturers use well established products and that the design, installation and commissioned are in line with industry good practices.

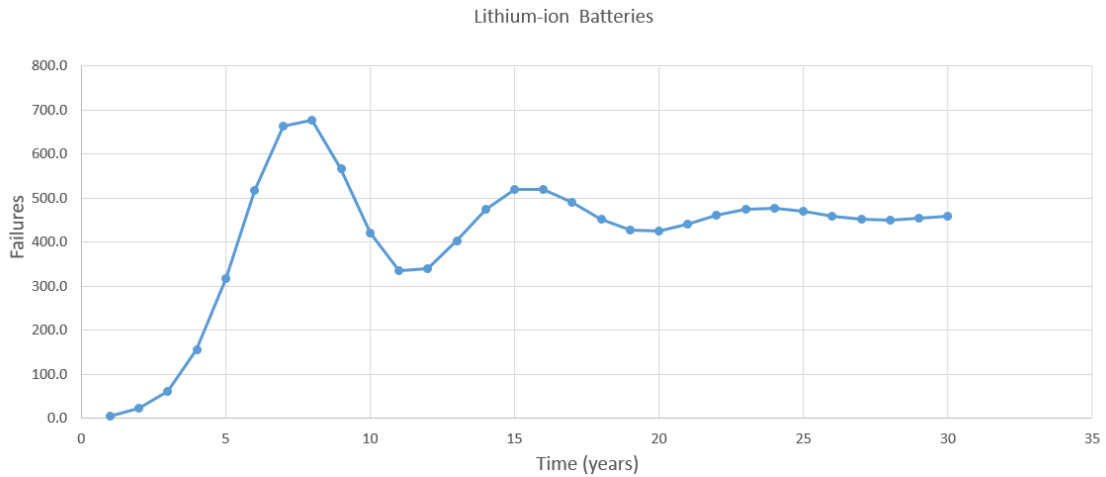
Table 4 below outlines the failure rates for the different technologies of PV tracker components applicable to the Case Study and PVTrax. It summarises the annual random failures rates and normal distributions (mean and standard deviation) defined by RINA for the most common single-axis tracker component technologies used in the current PV market. The failure rates have been established based on our experience in working across the lifecycle of tracking systems across a range of geographies, research of available technical documentation on the common technologies used by the single-axis tracker manufactures including reliability standards, technical papers and manufacturer recommendations. RINA considers its reliability modelling criteria to be in line with industry expectation and within the averaged range recommended by other well-known PV solar independent engineers, although any failure rate assumptions will come with uncertainties. The failure rates shown in Table 4 are captured in the lifetime cost assessment discussed in Section 4.

**Table 4: Corrective maintenance failure profile model based on RINA’s Methodology**

Technology type	Annual Random Failure Rate	Mean lifetime [years]	Standard deviation [years]
Brushless drive motors (both trackers)	0.10%	30	5
Transmission units - Worm gear (Tracker A) - Slew drive (Tracker B)	0.03%	35	10
Transmission units - Gear rack and joints (Tracker A)	0.01%	40	5
Bearings (both trackers)	0.01%	35	10
Harmonic dampers (both trackers)	0.10%	20.5	5
Electronics (both trackers) - Motor controllers - Master controllers - Data loggers	0.10%	17.5	5
Anemometer (Tracker B)	1.00%	12	3
Lithium-ion battery (Tracker B)	0.15%	7	2
Battery charger (Tracker B)	0.10%	15	5
Solar module (Tracker B)	0.05%	40	10

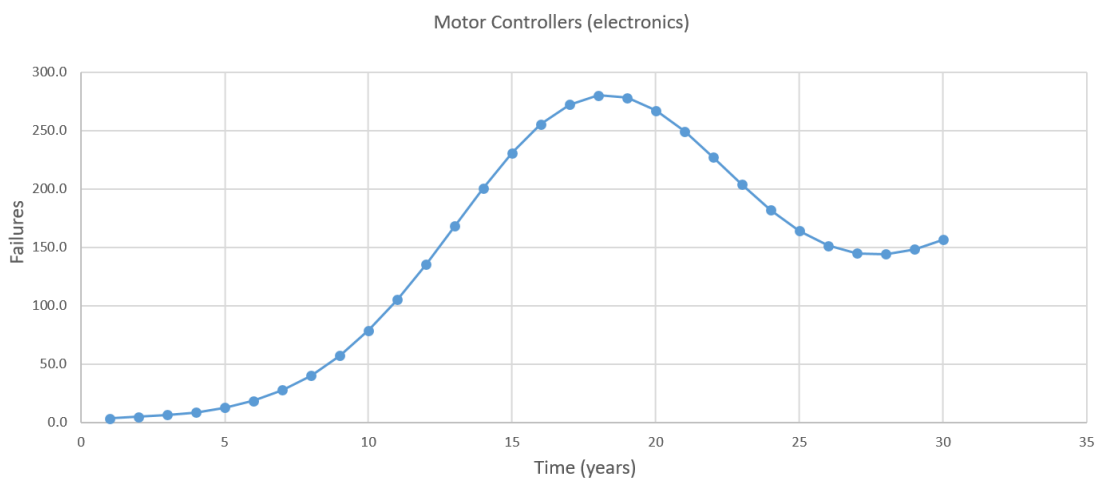
Figure 8 and Figure 9 outline examples of failures profile generated by PVTrax. Each graph includes both annual random failures and lifetime failures (Gaussian distribution) in combination. The model tracks what happens to each component unit along the lifetime of the PV plant, resetting their lifetime profile on component replacement.

**Figure 8: Lifetime failure profile of the Lithium-ion batteries for a population of 3914 batteries**



- Random annual failure rate: 0.15%;
- Normal Distribution: Mean lifetime = 7 years; Standard deviation = 2 years
- Averaged number of replacements in 30 years = 3.6 times

**Figure 9: Lifetime failure profile of the Motor Controllers (electronics) for a population of 3914 controllers**



- Random annual failure rate: 0.10%;
- Normal Distribution: Mean lifetime = 17.5 years; Standard deviation = 5 years
- Averaged number of replacements in 30 years = 1.2 times

Assumptions and information in Table 3 and Table 4 are also discussed in Appendix C.1 including some extended reasoning.

### 3.3.3 Notes on failure rate assumptions

The Methodology assumes that Tracker A and Tracker B have equivalent quality of components in line with industry good practice. Lifetimes of components in Table 4 have been defined based on a reasonable technological classification only. There is no differentiation in the lifetimes of the components assumed for brand, product capacity or quality. Although lifetimes are also variable inputs to PVTrax to provide wider flexibility of analyses, figures in Table 4 are the recommended

default standard values. Changes to failure rate assumptions can have significant impacts and any change should be performed on the basis of in-depth research.

The Methodology assumes that there are equal numbers of failure points present for equivalent components in Tracker A or Tracker B. For example, wired and wireless controllers are both modelled as electronics and assumed to have equal numbers of potential failure points for each component, and weighted equally for number of potential failures. More detailed analysis of specific failure modes could be added to the tool as an extension of the tool's development.

RINA's Methodology assumes that master controller failures do not have a downtime impact, but only a cost impact. More detailed analysis of this assumption could be added to the tool as an extension of the tool's development.

RINA notes that operation and maintenance assumptions may be challenging to quantify as it will be affected significantly by factors including project location, O&M contracting strategy, vendor market penetration within a given geography, etc.

For the present Case Study, with relation to after-sales service, RINA has assumed that in the event of component failure, technician availability and response times would follow the same criteria across both solution providers, in order to provide like-for-like results.

It has been assumed that the Case Study project maintains suitable availability of spare parts on site. As such, no additional down times have been assumed with relation to ordering, shipping and transport to site for failed components.

Parts, shipping costs and labour replacement times have been substantiated on an independent review of prices from manufactures of both type of tracking architectures (including ARRAY's) and RINA's experience in projects in various geographies.

With regards to warranties, during the EPC warranty period (typically 2 years after successful commissioning) in the event of a PV tracker failure, procurement, component and labour costs are generally covered.

After the EPC warranty period and until the end of the PV tracker supplier warranty, procurement and component costs are covered but labour cost are charged as an operation and maintenance (O&M) extra cost. PV tracker suppliers generally provide within 10 to 20 years warranty on structural parts and 5 years warranty in moving parts (i.e. drive motors, transmission system, dampers, bearing) and electronics (e.g. controllers). After PV tracker supplier warranty, all replacement costs are charged by the O&M contractor.

In PVTrax, warranty periods are variable inputs to fit project needs. The above mentioned standard warranties for EPC (2 years) and PV tracker moving parts and electronics (5 years) have been assumed for the Case Study.

Preventive maintenance (frequency, material cost, labour cost) and corrective maintenance (component costs, shipping costs, repair cost, response time) are variable inputs and can be edited in the tool to reflect the specific project O&M assumptions.

Users of PVTrax are able to input their own warranties, spare parts and response time assumptions into the model, and are encouraged to perform such work considering the likely characteristics of the specific project under consideration.

## 4 Project Case Study Inputs and Assumptions

RINA has performed lifetime performance modelling for a selection of project scenarios in order to establish the relative performance of the ARRAY tracking system when a single row tracking solution is used for the same project parameters.

This Section defines the project specific assumptions and inputs used to underpin the Case Study. RINA has chosen the assumptions in an effort to ensure a fair and independent lifetime cost comparison between Tracker A and Tracker B.

### 4.1 System Specifications

A typical 3,510 kWp DC block has been modelled. The typical DC block is then scaled based on the PV plant DC capacity input in the tool. For the base case scenario modelled, a 100 MWp plant has been assumed. The details of the technology of modules and inverters are shown in Table 5

**Table 5: PV plant system specifications**

Components	System specifications
Module	CS6U325 MAX POWER (0.325 kWp)
Inverter	SunGrow SG2500HV (2,556 kW <sub>AC</sub> )
PV plant DC capacity	100 MWp
Total number of modules	307,692
Project lifetime	30 years
Typical block DC capacity	3,510 kWp (10,800 modules, 30 modules per strings)
Typical block AC capacity	2,562 kW (1 inverter with 360 strings per inverter)
AC/DC power ratio	1:1.40
Tracker array configuration	90 modules per row - Tracker A: 30 rows/tracker - Tracker B: 1 row/tracker
Range of Motion (ROM) Tracker A	±52°
Range of Motion (ROM) Tracker B	±60°
Ground Cover Ratio (GCR)	Base Case: 40% Variant: 28.5%
Tracking algorithm	Backtracking and diffuse tracking assessed

In addition to a standard backtracking tracking algorithm, a diffuse tracking algorithm has also been assessed to evaluate its potential yield improvements. A backtracking algorithm faces the trackers directly at the sun (except very early and late in the day when tracking angle is modified to prevent shading). Diffuse tracking also considers the percentage of diffuse irradiation in the atmosphere, and sets optimised tracking angles under cloudy conditions.

Flat land has been assumed for the Case Study. In sites with complex topography, distributed systems capable of optimising the angle of each tracker (row) independently may have enhanced theoretical generation due to the optimisation of the inter-row shading, especially in non-cloudy locations where backtracking is the principal algorithm used.

## 4.2 Energy Yield Assessment

A suitable site for the assessment was chosen for the comparative Case Study upon agreement with ARRAY to ensure a like-for-like comparison. A detailed explanation of the yield assessment is outlined within the RINA’s yield methodology. An overview of the yield assumptions and irradiance databases considered for this assessment are outlined in Appendix C.3.

For the assessment RINA has modelled a selection of Ground-Cover Ratio (GCR) assumptions for the site. This categorises a PV project design based on the ratio of module area to land area. GCR is hence strongly related to the pitch between each row. Given that inter-row shading increases with GCR there is some degree of variation in the estimated yield based on the difference in Range of Motion (ROM) for the two tracking solutions. Tracker B performed slightly better than Tracker A, especially for the lower GCR case (28.5%), due to its wider ROM ( $\pm 60$  degrees vs  $\pm 52$  degrees) and the assumption of flat land. It is noted that Tracker A’s ROM can be extended from 52 to 62 degrees as an option. In projects with irregular topography, systems with greater ROM may present greater inter-row shading losses (mainly at the first and last hours of the day), reducing their potential advantage over systems with lower ROM. This statement is true when standard tracking algorithms (backtracking or true tracking) are used. There are already manufacturers of distributed systems with proprietary tracking algorithms capable of positioning each row independently at the appropriate angle to prevent inter-row shading which technically solves this problem at the cost of introducing additional complexity to control logic.

Generally, systems with wider ROM do require increased support columns heights (to comply with minimum module clearance to ground) incurring increased wind loads and additional structural costs. Therefore, although a system may support wider ROM, specific site constraints (e.g. irradiation profile, topography, wind load conditions) may influence on the selection of the optimal ROM to optimise project LCOE.

In line with RINA’s PV tracker lifetime cost Methodology Report, the Case Study assumes equivalent tracker CAPEX for both tracking technologies, therefore only the effect of the ROM on plant production has been considered.

Table 6 provides an overview of the comparative performance of the tracking solutions for two tracking algorithms (backtracking and diffuse tracking) and GCRs. We note that the diffuse algorithm affects Tracker B slightly more favourably. In addition to the theoretical yield in the scenario of 100% availability (“theoretical”), production in the event of a PV tracker failure has also been established. The below “tracking issues” production values are used to establish plant performance in the event of a component failure resulting in the tracking system becoming non-functional and the array being held in a random fixed tilt position until remedial works can take place. The model defined in the Methodology to determine the “tracking issues” figures is outlined in Appendix C.3.

**Table 6: Estimated yield for the modelled scenarios (all figures in MWh/year) assuming ROM  $\pm 52$  degrees for Tracker A and  $\pm 60$  degrees for Tracker B**

	GCR = 0.4		GCR = 0.285	
	Diffuse-tracking	Back-tracking	Diffuse-tracking	Back-tracking
Tracker A (Theoretical)	213,692.23	213,448.89	221,039.97	220,670.04

	GCR = 0.4		GCR = 0.285	
Tracker B (Theoretical)	213,847.04	213,582.57	221,856.96	221,509.71
Tracker A (Tracking issues)	143,737.72	142,701.92	143,838.09	142,725.48
Tracker B (Tracking issues)	141,793.11	140,424.30	141,044.11	139,599.96

As can be seen from the above results, the Tracker B solution tends to outperform the multi-row Tracker A under normal operating conditions. The relative performance of the trackers is reversed in the instance of a component failure. This can be attributed to the larger ROM of Tracker B resulting in a greater impact on yield when a failure occurs at the extremes of the ROM. Increased inter-row shading at these extreme angles occurs for Tracker B due to an increased probability of failed array tilt angle being more vertical. Further detail on the yield modelling approach is presented in RINA's PV tracker lifetime cost Methodology Report [1].

A module degradation of 0.4% has been considered when assessing the lifetime net energy yield for each tracker. Figures in Table 6 are inputs to the model. Net energy yield, after considering losses due to trackers' unavailability can be seen in the model results shown in Section 5.

### 4.3 General assumptions common to both tracking technologies

The following assumptions (in line with the assumptions defined in the RINA's PV tracker lifetime cost Methodology Report [1]) have been made to allow for an objective cost comparison assessment:

- The PV plant design assumptions and electrical configuration, in particular the ones related to the PV tracker design (i.e. GCR, number of modules per row, modules per string and strings per inverter), are assumed to be the same for both tracking technologies and are in line with market standards and industry good practices. Hence, no specific differences related to the plant design are to be accounted for in the estimation of faulty components or potential loss of energy related to the PV trackers.
- A plant life of 30 years has been assumed, in line with the design life and PPA duration for most utility-scale PV plants.
- The same Project site solar resource, obtained as per RINA's energy yield methodology, have been used for the estimation of the energy yield generated by each tracker.
- The theoretical yield is an input to the lifetime cost estimation model, with Tracker B featuring a slightly greater yield than Tracker A. The energy yield assessment (EYA) figures are only applicable to this Case Study.
- It has been assumed that the site land is relatively flat and suitable for the installation of both single-axis tracking technologies. It is also assumed that there is sufficient developable area to allocate 100 MWp of both tracking technologies.
- Two different GCR scenarios have been assessed (28.5% and 40%) for the purpose of evaluating the effect on the PV plant lifetime yield and to quantify the theoretical benefits of the additional range of motion (ROM) of Tracker B, for the specific location of the Project.
- The faults of the different components responsible of the movement of the tracker have been considered on the estimation of the energy underperformance, according to the aforementioned RINA's PV tracker lifetime cost Methodology (see references in Section 7, item [1])

- The estimation of CAPEX and non-tracker-OPEX of the PV plant is not within the scope of the Methodology. Since the objective of the Methodology is to compare single-axis tracker technologies on the basis of their operational lifetime cost and loss of generation, common non-tracker costs (CAPEX and OPEX) and trackers' CAPEX have been assumed as known inputs for the Case Study.
- ROM has only been considered from the perspective of energy yield (tracker CAPEX has been assumed equivalent).
- Spare parts of all PV tracker components that may need replacement have been assumed to be available on site for both tracking technologies. Therefore, delivery time have not been considered when estimating tracker unavailability in the event of a component failure impacting on the tracker operation.
- Support columns and their foundations are assumed to last for the lifetime of the PV plant.
- Faulty PV tracker components are assumed to be replaced (not repaired).
- Inspections of fasteners, torque marks, nuts, module clamps and corrosion are assumed to be equivalent for both tracking technologies and included as a general preventive maintenance task within the O&M contract.
- PV tracker components failures occurring during the lifetime of the PV plant are assumed to be adequately detected and addressed in a yearly basis. Reasonable response times have been assumed to replace faulty components affecting the operation of the tracker (e.g. drive motors, slew drives, worm gears, rack gears, driveline joints, motor controllers, batteries, batteries chargers and solar modules).

### 4.3.1 Additional inputs to PVTrax

Assumptions common (non-tracker CAPEX, non-tracker OPEX, warranties, financial parameters, etc.) and specific for each tracking architecture (e.g. component costs) are summarised in the tables below.

**Table 7: Common additional inputs and assumptions to the model**

Common inputs to both trackers	
Mowing cost	
-No drivelines	0.40 \$/kWp
-Disconnecting drivelines	0.42 \$/kWp
-Fixed drivelines or cable trays used	0.44 \$/kWp
Cleaning cost (tracker based)	
-No drivelines	0.80 \$/kWp
-Disconnecting drivelines	0.84 \$/kWp
-Fixed drivelines or cable trays used	0.88 \$/kWp
Labour cost (technician)	30.00 \$/hour
Warranties	
-EPC	2 years (from commissioning)
-Tracker Supplier (moving parts and electronics)	5 years (from commissioning)
PV plant CAPEX (PV tracker excluded)	900.00 \$/kWp
PV plant OPEX (PV tracker excluded)	6.00 \$/kWp
Tracker CAPEX (assumed the same)	120.00 \$/kWp
Discount rate (ARRAY input based on site location)	6.30%

Common inputs to both trackers	
Inflation (ARRAY input based on site location)	2.50%
Price of electricity (ARRAY input based on site location)	0.05 \$/kWh

**Table 8: Component replacement costs and response times**

Component Type	Component Cost (\$)	Delivery cost (\$)	Labour Time (hours)	Labour quantity (# people)	Response Time <sup>8</sup> (natural days / hours > 0 W/m <sup>2</sup> )
<b>Tracker A</b>					
Drive motor	2,000	200	4	2	5 days / 62.1 hours
Worm gear	325	50	1.5	1	15 days / 186.4 hours
Gear rack	110	100	0.5	2	15 days / 186.4 hours
Joints	75	20	0.25	1	5 days / 62.1 hours
Bearing	30	5	2	2	N/A
Harmonic damper	30	20	0.5	1	N/A
Motor controller	400	15	2	1	5 days / 62.1 hours
Master controller	875	15	2	1	N/A
<b>Tracker B</b>					
Drive motor	85	15	0.5	1	15 days / 186.4 hours
Slew drive	325	50	2	2	15 days / 186.4 hours
Bearing	30	5	2	2	N/A
Harmonic damper	30	20	0.5	1	N/A
Motor controller	225	10	1	1	15 days / 186.4 hours
Master controller	1,000	15	4	1	N/A
Solar module	75	10	0.5	1	15 days / 186.4 hours
Battery charger	25	10	0.5	1	15 days / 186.4 hours

<sup>8</sup> Apply only to components affecting the tracker availability (movement of the tracker)

Component Type	Component Cost (\$)	Delivery cost (\$)	Labour Time (hours)	Labour quantity (# people)	Response Time <sup>8</sup> (natural days / hours > 0 W/m <sup>2</sup> )
Battery	30	10	0.5	1	15 days / 186.4 hours
Additional anemometers	200	10	2	1	N/A
Additional data loggers	700	15	2	1	N/A
Additional controllers	1,000	15	2	1	N/A
Additional solar modules	75	10	0.5	1	N/A
Additional battery chargers	25	10	0.5	1	N/A
Additional batteries	30	10	0.5	1	N/A

### 4.3.2 System components and quantities

Based on the distinguishing features of the tracking solutions discussed in Sections 2 and 3, RINA has based the assessment on the following breakdown of key components calculated by PVTrax based on the assumed inputs (site size, electrical configuration and PV tracking architectures selected).

**Table 9: Break down of component numbers assumed for each tracking solution**

EU type	Tracker A Component quantities	Tracker B Component quantities
Drive motor (including the drive gear) - AC or DC brushless	114	3,419
Transmission unit - Worm gear	3,419	N/A
Transmission unit - Gear rack	3,419	N/A
Transmission unit - Joints	6,610	N/A
Transmission unit – Slew drive	N/A	3,419
Bearing	37,607	37,607
Harmonic damper	6,838	6,838
Motor controller	114	3,419
Master controller	19	34.2
Mowing - Disconnecting drivelines	Yearly	Yearly
Cleaning Tractor based - Disconnecting drivelines	Yearly	Yearly
Power supply - Solar module	N/A	3,419

EU type	Tracker A Component quantities	Tracker B Component quantities
Power supply - Battery charger	N/A	3,419
Power supply - Battery	N/A	3,419
Active Stowing System - Additional anemometers	N/A	4
Active Stowing System - Additional data-loggers	N/A	4
Active Stowing System - Additional controllers	N/A	1
Active Stowing System - Additional solar modules	N/A	4
Active Stowing System - Additional battery charger	N/A	4
Active Stowing System - Additional battery	N/A	4
Mowing -Disconnecting drivelines (Tracker A) -No drivelines (Tracker B)	Yearly	Yearly
Cleaning Tractor based -Disconnecting drivelines (Tracker A) -No drivelines (Tracker B)	Yearly	Yearly

## 5 Results and Discussions

### 5.1 Base Case Scenario (GCR = 0.4)

Table 10 provides headline comparative results for Tracker A vs Tracker B in the scenario described above. In the table, results are compared for Tracker A vs Tracker B, with the lower cost tracker shown in green and the higher cost tracker in red. Key findings of Table 10 are as follows:

- At tracker level, the discounted lifetime cost of ownership of Tracker B is higher than Tracker A, with a relative difference of 7.32% (\$1,063,606.48 more expensive for the 100 MWp Case Study project, i.e. a lifetime cost difference of ~ 0.0106 \$/Wp). At the PV plant level, the lifetime cost of the PV plant (discounted) is 1.02% higher when using Tracker B.
- On a NPV and LCOE basis, Tracker A presents small but significant advantages over Tracker B (1.18% lower LCOE and 3.11% higher NPV).
- Main areas of difference between Tracker A and Tracker B are reduced OPEX for Tracker A, primarily due to reduction in failure rates due to use of a smaller number of components in its centralised solution and the longer lifetime of the components with higher impact on tracker availability and cost (worm gears, gear racks and joints of the transmission system). These reduced failure rates also led to improved availability and hence generation.
- Differences between systems when considering backtracking vs diffuse tracking algorithms are relatively immaterial. *Italic figures* have been used in Table 10 to demonstrate where results differ due to the tracking algorithm used.

Further detail on comparative results is provided below.

**Table 10: Comparative results – GCR 0.4, 100 MWp**

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference	Tracker A	Tracker B	Absolute Difference	Relative Difference
Tracking algorithm	Backtracking Algorithm				Diffuse Algorithm			
Headline results								
Discounted Total Tracker Lifetime	13,473,348.78	14,536,955.26	1,063,606.48	7.32%	13,473,348.78	14,536,955.26	1,063,606.48	7.32%

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference	Tracker A	Tracker B	Absolute Difference	Relative Difference
Cost (Absolute) (\$)								
Discounted Tracker Lifetime Cost (\$/MWp)	134,733.49	145,369.55	10,636.06	7.32%	134,733.49	145,369.55	10,636.06	7.32%
<i>LCOE (c\$/kWh)</i>	3.56	3.60	0.04	1.18%	3.56	3.60	0.04	1.17%
<i>NPV PV Project(\$)</i>	41,775,764.89	40,474,521.95	1,301,242.93	3.11%	41,941,912.18	40,660,434.87	1,281,477.31	3.06%
<b>Tracker OPEX</b>								
PV tracker OPEX - Fixed Costs (Discounted)	1,295.33	492.58	802.75	61.97%	1,295.33	492.58	802.75	61.97%
PV tracker OPEX - Variable Costs (Discounted)	13,438.16	24,876.97	11,438.82	45.98%	13,438.16	24,876.97	11,438.82	45.98%
PV tracker OPEX - Total Costs (Discounted)	14,733.49	25,369.55	10,636.06	41.92%	14,733.49	25,369.55	10,636.06	41.92%
<b>Tracker Energy Losses</b>								
<i>Lifetime Energy Tracking Losses (Discounted)</i>	0.04%	0.27%	0.23%	84.52%	0.04%	0.26%	0.22%	84.41%
<b>PV Plant Costs</b>								

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference	Tracker A	Tracker B	Absolute Difference	Relative Difference
Lifetime Cost of the PV plant (Absolute) (Discounted)	103,473,377.44	104,536,983.92	1,063,606.48	1.02%	103,473,377.44	104,536,983.92	1,063,606.48	1.02%
Lifetime Cost of the PV plant (per MWp) (Discounted)	1,034,733.77	1,045,369.84	10,636.06	1.02%	1,034,733.77	1,045,369.84	10,636.06	1.02%
<b>PV Plant Generation</b>								
<i>Net Lifetime Energy Generated (\$ Revenue) (Discounted)</i>	145,249,142.33	145,011,505.88	237,636.45	0.16%	145,415,289.63	145,197,418.80	217,870.83	0.15%
<i>Net Lifetime Energy Generated (MWh) (Discounted)</i>	2,904,982.85	2,900,230.12	4,752.73	0.16%	2,908,305.79	2,903,948.38	4,357.42	0.15%
<i>Net Lifetime Energy Generated (MWh) (Undiscounted)</i>	6,041,748.62	6,028,759.88	12,988.74	0.21%	6,048,675.73	6,036,561.41	12,114.32	0.20%

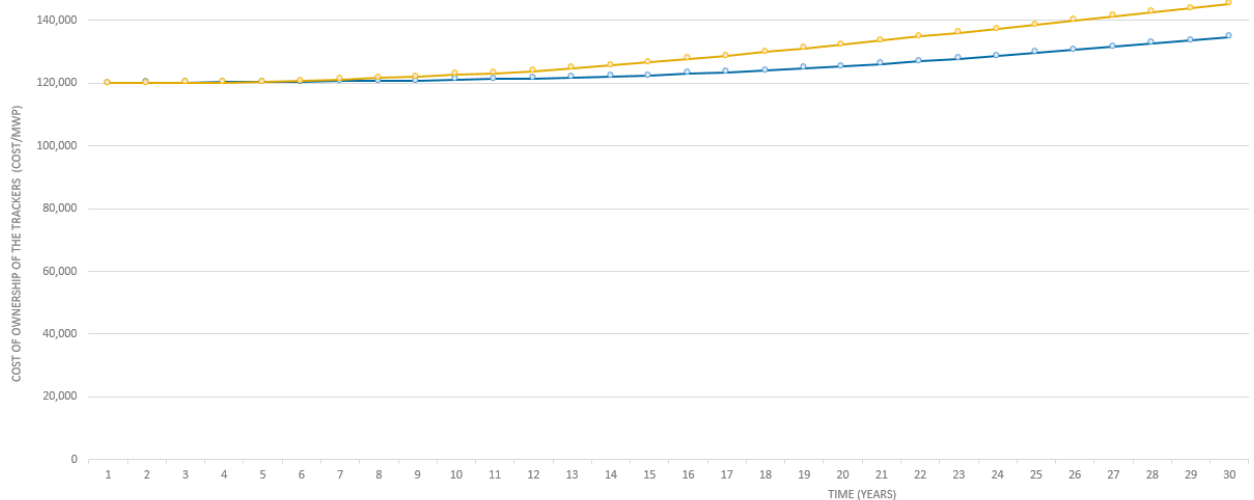
Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference	Tracker A	Tracker B	Absolute Difference	Relative Difference
<b>Availability</b>								
PV tracker Lifetime Availability (Average over lifetime)	99.84%	98.99%	0.85%	0.85%	99.84%	98.99%	0.85%	0.85%
Worst Year PV tracker Availability (Minimum value)	99.30%	98.44%	0.86%	0.86%	99.30%	98.44%	0.86%	0.86%

### Lifetime costs

Figure 10 demonstrates the year-on-year PV tracker lifetime costs for both tracking solutions. A CAPEX of 120.00 \$/kWp has been assumed for both trackers. While the both tracking solutions initially are quite equal, from the below graph, it is evident that Tracker A becomes economically favourable after year 5. This is largely based on the input modelling assumptions which considered a five year warranty period would be offered by the tracker manufacturers (material and shipment costs of faulty tracker components are covered by the tracker suppliers during the tracker supplier warranty period). The deviation from year 5 is due to expiry of the warranty period and hence exposure of the PV project to all preventative and corrective maintenance costs associated with the trackers.

**Figure 10: NPV tracker lifetime costs (CAPEX + OPEX), GCR 0.4, 100 MWp<sup>9</sup>**

**Lifetime cost difference of ~ 0.0106 \$/Wp.**

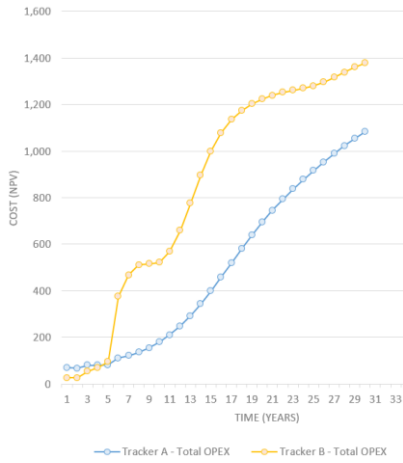


Following the end of this warranty period we note that there are material costs associated with the replacement of components as they reach end of life. For the Tracker B solution, components with lower assumed mean lifetime before failure (such as the battery) play a significant role in increasing the lifetime costs. Further breakdown of the fixed and variable OPEX costs are provided in Figure 11 to Figure 13.

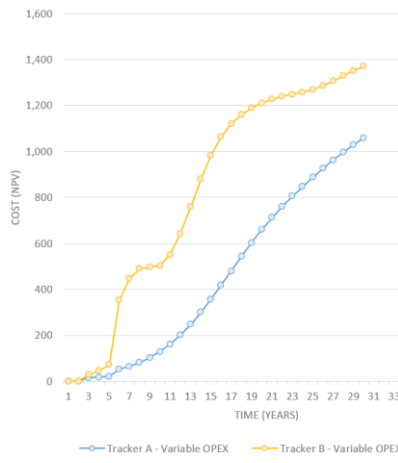
Although Tracker A features higher specific fixed operational costs (mainly due to higher mowing and cleaning costs) variable costs are significantly greater in Tracker B due to the contribution of components with shorter lifetime (e.g. batteries) together with greater amount of components. Over the first five years both trackers present equivalent costs (see Figure 10) with Tracker A slightly more expensive due to greater fixed annual costs (see Figure 13). However, after the expiration of the 5 year supplier warranty, the order of cost curves are reversed with Tracker B presenting higher costs from year 6 to the end of the lifetime of the plant (see Figure 12),

<sup>9</sup> Cost results common for backtracking and diffuse tracking algorithms and as such have not been duplicated.

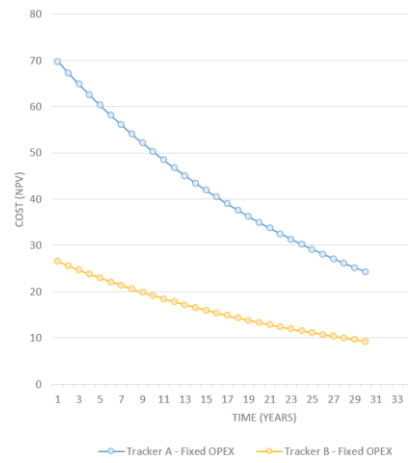
**Figure 11: Total OPEX**



**Figure 12: Variable OPEX**



**Figure 13: Fixed OPEX**

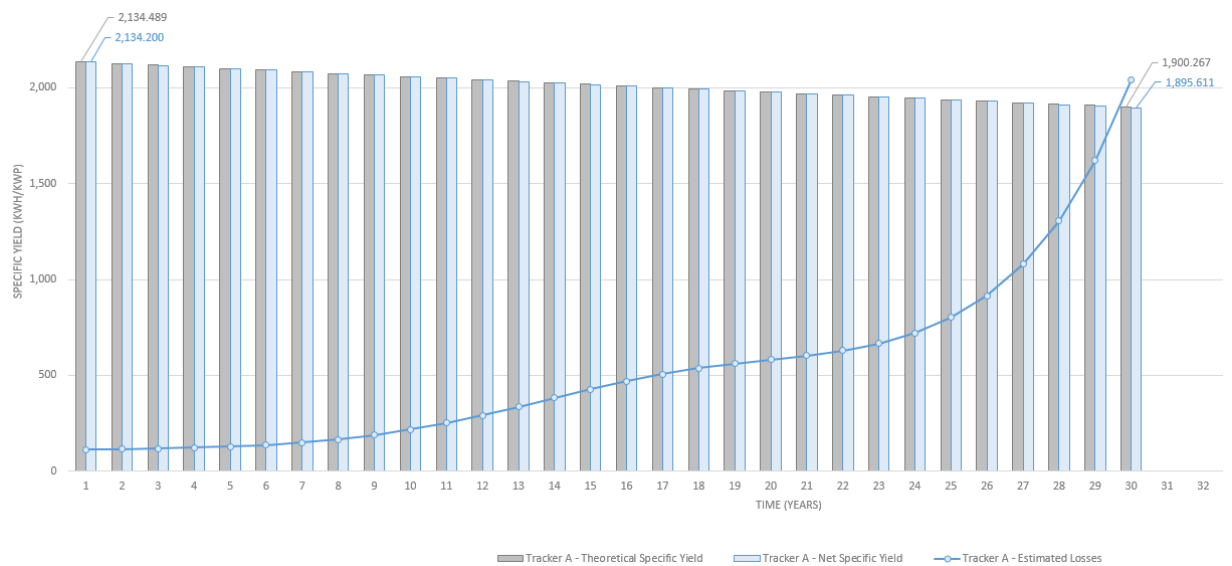


**Lifetime performance**

The figures below provide an overview of the yield performance of the PV plant over the 30-year project life considering both tracking technologies. As can be seen in Figure 14 and Figure 15, the estimated losses for Tracker A and B follow different distribution curves. This is due to the associated failure rates of the components (as further detailed in Table 9). In Tracker A, due to the fact that most of components that can affect tracker availability have long lifetimes (worm gears, gear racks and joints), and since the quantity of electronics and motors is 30 times lower, the estimated losses curve increases steadily over time with significant impact at the end of the plant lifetime.

Tracker B has a variety of components with shorter lifetime, directly affecting the availability of the tracker (30 times more motors and controllers plus the 30 times the addition of new components with short lifetimes, i.e. batteries and battery chargers) hence the multiple peaks in the curves.

**Figure 14: PV Plant Lifetime Energy Generation – Tracker A – GCR 0.4 with backtracking**



**Figure 15: PV Plant Lifetime Energy Generation – Tracker B – GCR 0.4 with backtracking**

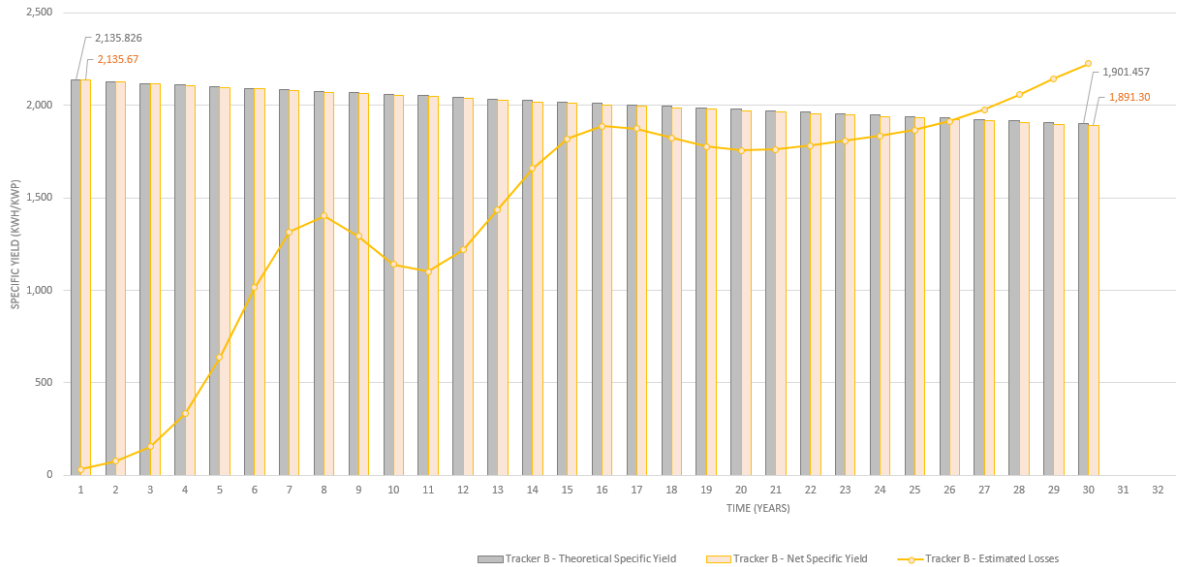


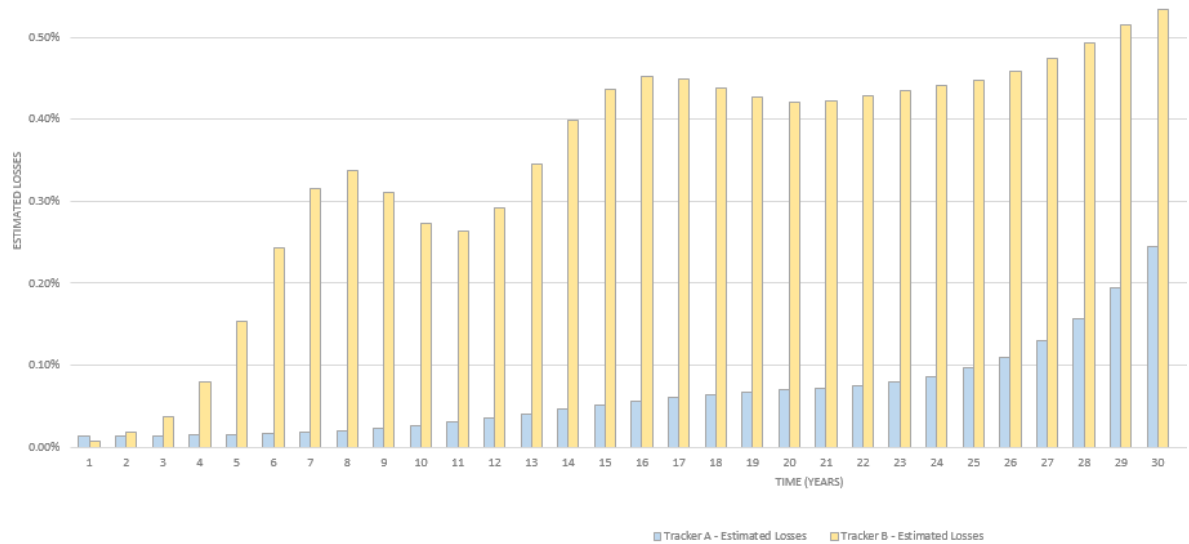
Figure 16 demonstrates how each tracking technology deviates from the theoretical yield over the course of the project life.

Tracker B has lower granularity (smaller impacted capacity in the event of a tracker failure) but features significant amount of failures, and therefore losses, from the early start through to the end of the life of the PV plant. Tracker A, although having a wider granularity (tracker failures have higher impact on production as a failure of the centralised system affects multiple rows at once) has less components that can cause a tracker failure (30 times less motors or controllers) and the components which present higher quantities and could impact on the tracker availability are assumed to have longer lifetime expectancies (e.g. worm gear, gear rack, joints for Tracker A vs batteries or battery chargers for Tracker B).

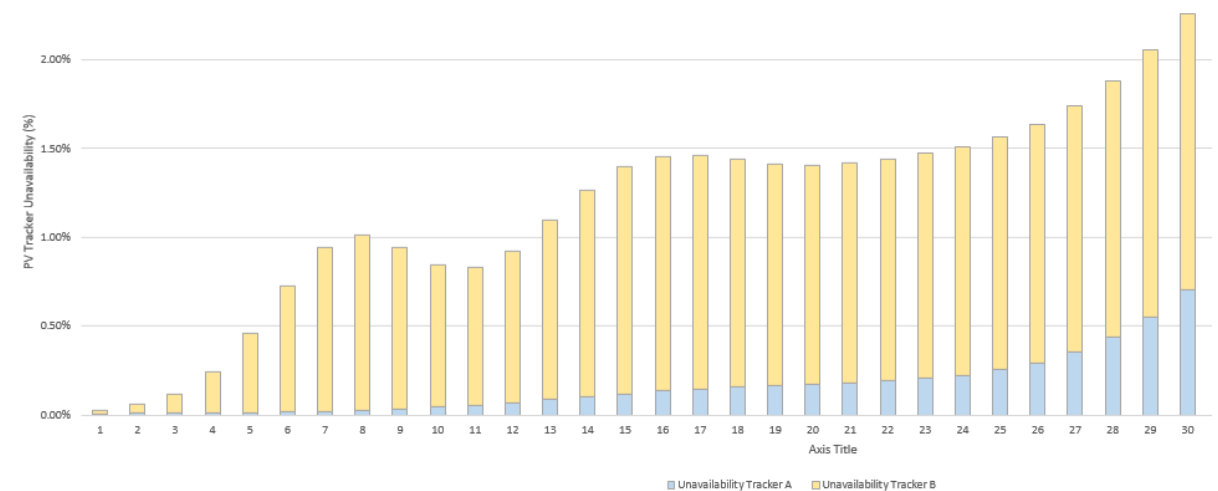
We note that at the end of the lifetime of Tracker A, since mechanical components are approaching their life expectancies, the plant starts to suffer greater unavailability figures. However as these failures occur later in the lifetime of the Project, losses are more heavily discounted. Hence, while both trackers have similar net lifetime yield figures, Tracker A performs better on a LCOE and NPV basis.

Performance results for the diffuse tracking algorithm are materially similar to those presented for the back tracking results in terms of the trends realised with a minor improvement for Tracker B. The figures for the diffuse tracking results are presented in Appendix A.1.

**Figure 16: Deviation from theoretical yield – GCR 0.4, 100 MWp with backtracking**



**Figure 17: PV tracker unavailability (annual)**



## 5.2 Sensitivity analysis

RINA has undertaken indicative sensitivity analysis in order to demonstrate how varying a single input parameter can impact the results provided above.

The three sensitivity scenarios have been established by ARRAY and conducted by RINA to provide insight as to how revisions to the Case Study Project design would impact the performance of the given tracking solutions:

1. Both trackers with cable trays (impact on mowing and cleaning costs)
2. Increasing components' prices
3. Reducing Ground Cover Ratio

These sensitivities are discussed in greater detail in the subsequent sections and independently deal with varying three key concepts which can influence the suitability of a given tracker. Sensitivities 1 and 2 examine how adjusting the operational costs impact the economic metrics. Sensitivity 3 examines how adjusting the project performance and associated yield impacts the preferred solution. The three sensitivity scenarios are provided for context and we note that the modelling tool should be used in order to provide insight when considering the relative impact on a specific project.

Further sensitivities which could be modelled using PVTrax (but have not been included as part of this assessment), include:

- O&M costs (e.g. labour, failed component replacement cost)
- Performance
  - Failed component response times
  - Solar resource (different location)
- Project capacity / Module power ratings
- Tracking system CAPEX
- Tracker range of motion
- Extended warranties of key components (e.g. batteries)
- Project site topography and near shading
- Proprietary tracking algorithms (yield figures to be provided - input)

### Sensitivity 1: Cable trays in both trackers

The first sensitivity examines the impact of introducing cable trays to both trackers system designs, which may be necessary on sites with hard land where trenching is complex and expensive, with high ground moisture, near ground-level water tables, or to attempt to reduce costs.

Mowing and cleaning costs are PV plant OPEX. However, as described in RINA's Methodology [1], depending on the tracker architecture, mowing and/or cleaning costs are expected to vary slightly. As shown in Table 7, "No drivelines" systems (Tracker B) are assumed to have the cheapest mowing and cleaning<sup>10</sup> costs (\$0.40 / kWp and \$0.80 / kWp) and "Non-disconnecting drivelines" systems the most expensive (\$0.44 / kWp and \$0.88 / kWp). Intermediate prices (\$0.42 / kWp and \$0.84 / kWp) have been assumed for "Disconnecting drivelines" (Tracker A).

In order to isolate tracker OPEX to solely tracker differences, only *the difference (extra cost)* in cleaning and mowing costs when compared to the cheapest case ("No drivelines" systems) is accounted as tracker OPEX (as opposed to PV plant OPEX). In the base case of this Case Study, only Tracker A has Tracker OPEX for mowing and cleaning, with these additional costs (\$0.02 / kWp and \$0.04 / kWp respectively) included due to the need to connect and disconnect drivelines.

In this sensitivity analysis, both trackers have cable trays (equivalent to "Non-disconnecting" drivelines as per Table 7), and the extra mowing and cleaning cost associated with the extra complexity of the mowing and cleaning works (assumed as \$0.04 / kWp for mowing and as \$0.08 / kWp for cleaning, regardless of centralised or distributed scenario) has been accounted for both Tracker A and B as additional tracker OPEX.

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<sup>10</sup> Assuming tractor based mowing and cleaning

This sensitivity analysis shows that, under same cleaning and mowing costs, preventive costs of Tracker A are 11.5% lower than Tracker B. As such, due to the increased fixed costs, the Tracker Lifetime Costs have increased, resulting in a lower NPV of the Tracker B solution when compared with the base case scenario.

The performance of the Trackers does not change due to this sensitivity analysis.

Increased O&M costs due to the cable trays design have resulted in Tracker A offering a solution which is even more favourable than Tracker B in the base case scenario.

**Table 11: Comparative results – GCR 0.4 with backtracking algorithm (Sensitivity 1)**

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
<b>Headline results</b>				
Discounted Total Tracker Lifetime Cost (Absolute) (\$)	13,584,876.55	14,760,010.80	1,175,134.25	7.96%
Discounted Tracker Lifetime Cost (\$/MWp)	135,848.77	147,600.11	11,751.34	7.96%
LCOE (c\$/kWh)	3.57	3.61	0.05	1.28%
NPV PV Project(\$)	41,657,019.44	40,251,466.41	1,405,553.03	3.37%
<b>Tracker OPEX</b>				
PV tracker OPEX - Fixed Costs (Discounted )	2,410.61	2,723.14	312.53	11.48%
PV tracker OPEX - Variable Costs (Discounted)	13,438.16	24,876.97	11,438.82	45.98%
PV tracker OPEX - Total Costs (Discounted)	15,848.77	27,600.11	11,751.34	42.58%
<b>PV plant Costs</b>				
Lifetime Cost of the PV plant (Absolute) (Discounted)	103,584,905.22	104,760,039.47	1,175,134.25	1.12%
Lifetime Cost of the PV plant (per MWp) (Discounted)	1,035,849.05	1,047,600.39	11,751.34	1.12%

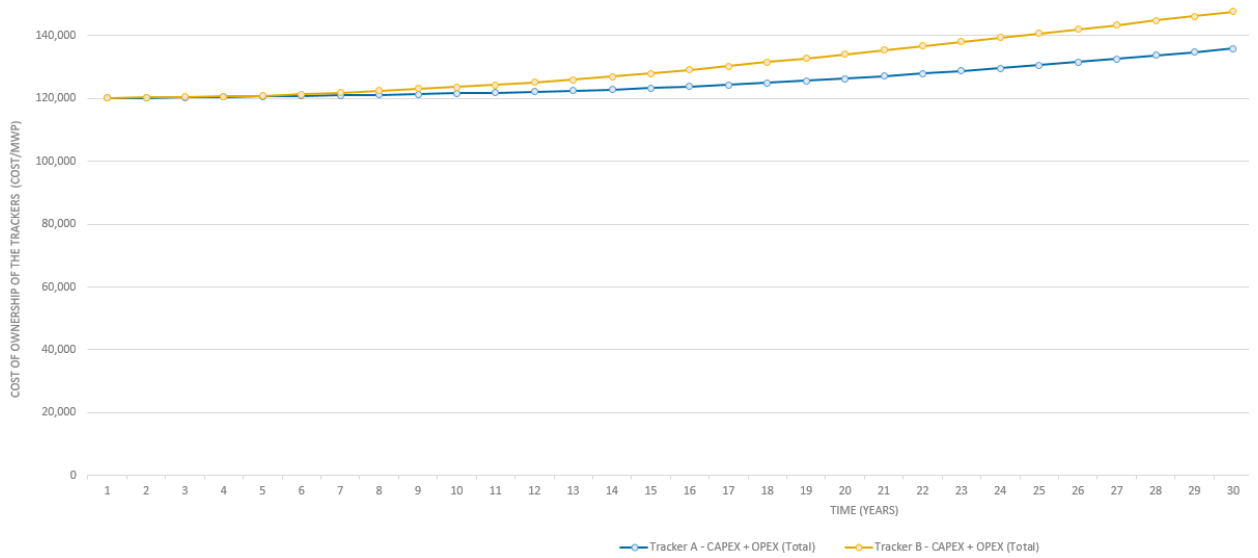
Tracker energy losses, PV plant generation and availability are not shown since they remain equal (only cost variations with Sensitivity 1 are noted).

An additional table of results for the diffuse tracking scenario are provided in Appendix A.2.

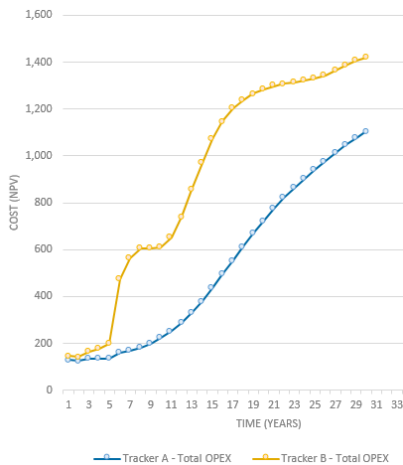
### Lifetime costs

As detailed within Section 5, similar trend graphs are realised for the Sensitivity 1 scenario. Graphs affected by the sensitivity analysis are presented below.

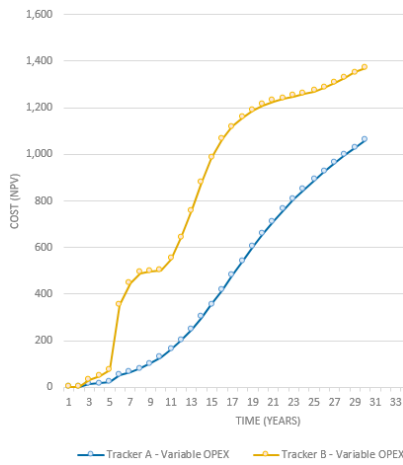
**Figure 18: NPV tracker lifetime costs (CAPEX + OPEX), GCR 0.4, 100 MWp**



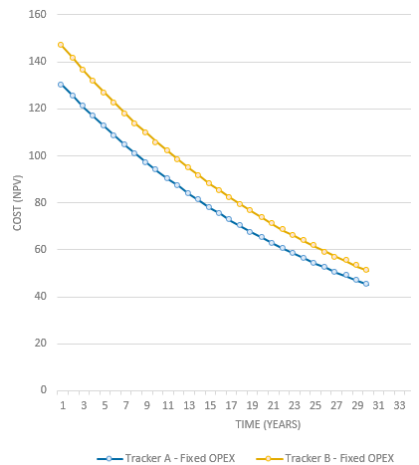
**Figure 19: Total OPEX**



**Figure 20: Variable OPEX**



**Figure 21: Fixed OPEX**



**Sensitivity 2: Increasing Component Prices**

Component prices may vary with project location (country), manufacturer to manufacturer, purchase volume, the O&M sourcing strategy and margin, etc.

Reasonably competitive component prices for both trackers have been assumed for the base case scenario. This second sensitivity analysis intends to capture the impact of the use of higher component prices.

Higher component prices have been considered for this sensitivity scenario (refer to Table 12). A factor of 2 has been applied to all base case component prices. Shipping costs and all other design assumptions have remained constant from the base case scenario described in Section 5.

**Table 12: Higher component costs**

Component Type	Component Cost (\$)
<b>Tracker A</b>	
Drive motor	4,000
Worm gear	650
Gear rack	220
Joints	150
Bearing	60
Harmonic damper	60
Motor controller	800
Master controller	1750
<b>Tracker B</b>	
Drive motor	170
Slew drive	650
Bearing	60
Harmonic damper	60
Motor controller	450
Master controller	2,000
Solar module	150
Battery charger	50
Battery	60
Additional anemometers	400
Additional data loggers	1,400
Additional controllers	2,000
Additional solar modules	150
Additional battery chargers	50
Additional batteries	60

In this higher component cost scenario, corrective maintenance costs for both trackers increase. However Tracker B experiences a higher cost increase, leading to an increased variable cost differential of around 5%.

In Sensitivity 2, the discounted lifetime cost of ownership of Tracker B has increased compared to Tracker A, with a relative difference of 11.58% (\$1,831,826.04 more expensive for the 100 MWp Case Study project, i.e. a lifetime cost difference of ~ 0.0183 \$/Wp). At the PV plant level, the lifetime cost of the PV plant (discounted) is 1.73% higher when using Tracker B.

On a NPV and LCOE basis, Tracker A presents small but significant advantages over Tracker B (1.89% lower LCOE and 5.01% higher NPV).

The performance of the trackers does not change due to this sensitivity analysis.

Compared to the base case scenario, increased O&M costs due to increased component costs have resulted in Tracker A offering a solution which is even more favourable than Tracker B.

**Table 13: Comparative results – GCR 0.4 with backtracking algorithm (Sensitivity 2)**

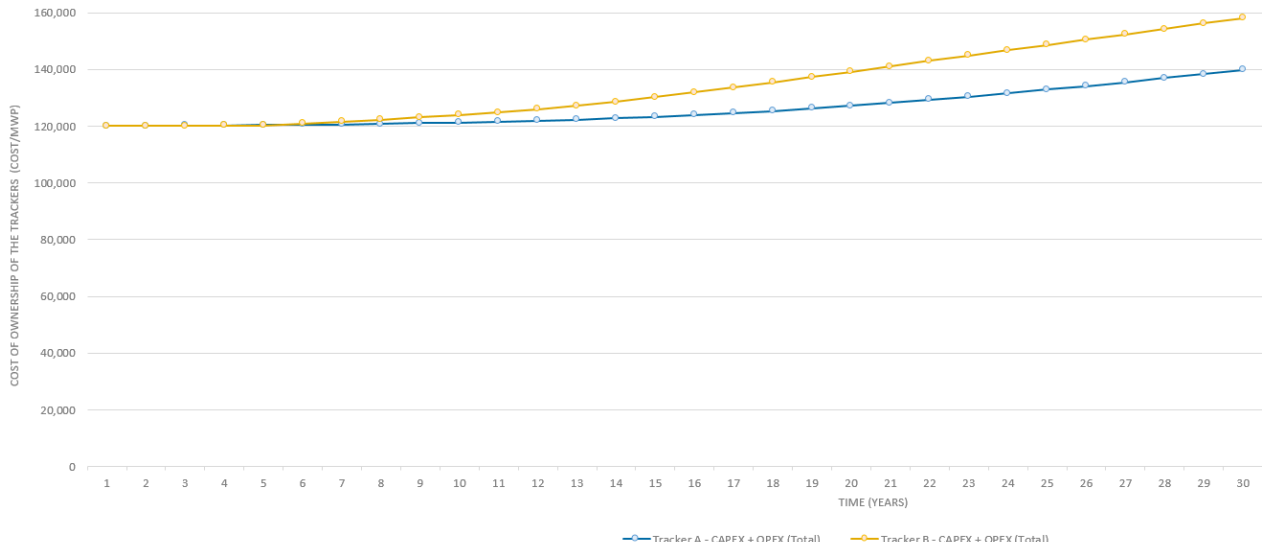
Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
<b>Headline results</b>				
Discounted Total Tracker Lifetime Cost (Absolute) (\$)	13,980,884.83	15,812,710.87	1,831,826.04	11.58%
Discounted Tracker Lifetime Cost (\$/MWp)	139,808.85	158,127.11	18,318.26	11.58%
LCOE (c\$/kWh)	3.58	3.65	0.07	1.89%
NPV PV Project(\$)	41,268,228.83	39,198,766.34	2,069,462.49	5.01%
<b>Tracker OPEX</b>				
PV tracker OPEX - Fixed Costs (Discounted )	1,295.33	492.58	802.75	61.97%
PV tracker OPEX - Variable Costs (Discounted)	18,513.52	37,634.53	19,121.01	50.81%
PV tracker OPEX - Total Costs (Discounted)	19,808.85	38,127.11	18,318.26	48.05%
<b>PV plant Costs</b>				
Lifetime Cost of the PV plant (Absolute) (Discounted)	103,980,913.50	105,812,739.54	1,831,826.04	1.73%
Lifetime Cost of the PV plant (per MWp) (Discounted)	1,039,809.14	1,058,127.40	18,318.26	1.73%

Tracker energy losses, PV plant generation and availability are not shown since they remain equal (only cost variation with Sensitivity 1 are noted).

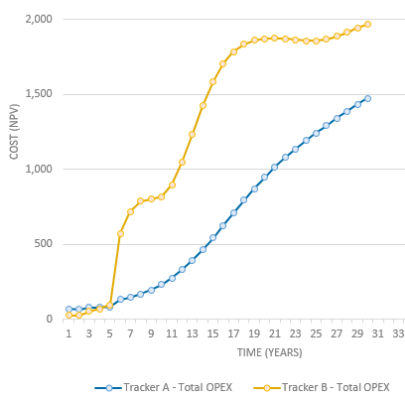
### Lifetime costs

As detailed within Section 5, similar trend graphs are realised for the Sensitivity 2 scenario. Graphs affected by the sensitivity analysis are presented below.

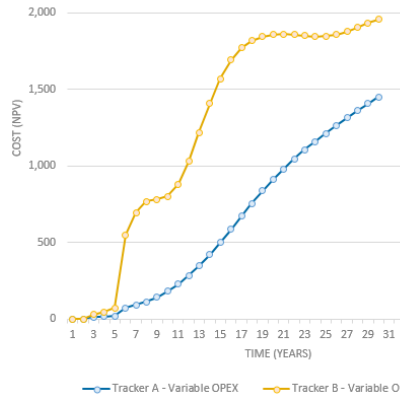
**Figure 22: NPV tracker lifetime costs (CAPEX + OPEX), GCR 0.4, 100 MWp**



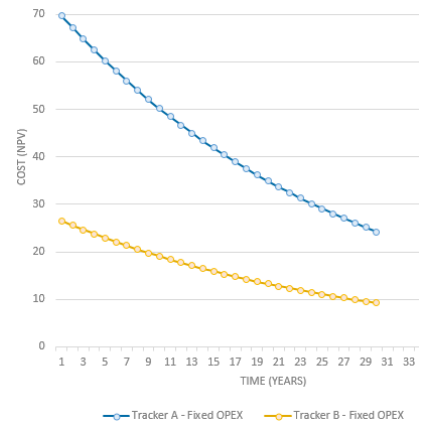
**Figure 23: Total OPEX**



**Figure 24: Variable OPEX**



**Figure 25: Fixed OPEX**



**Sensitivity 3: Ground Cover Ratio**

For the third sensitivity analysis, RINA has undertaken our assessment in a reduced GCR scenario. Table 14 outlines the results for the scenario with the GCR reduced from 0.4 to 0.285. All other design assumptions have remained constant from the base case scenario described in Section 5. However, with the reduced GCR (i.e. increased row spacing), there has been a material change in the comparative performance of the two tracker solutions.

Tracker B, with its increased range of movement realises a material increase in the net lifetime energy generation (both in terms of MWh and revenue) over the project life. We see the relative difference between Tracker A and Tracker B reverse from 0.21% (equal undiscounted net lifetime energy yield) in the base case scenario (GCR of 0.4) in favour of Tracker A, to 0.08% in favour of Tracker B. We note that the increase of the inter row spacing leads to a greater NPV, assuming no constraint on land availability or land costs.

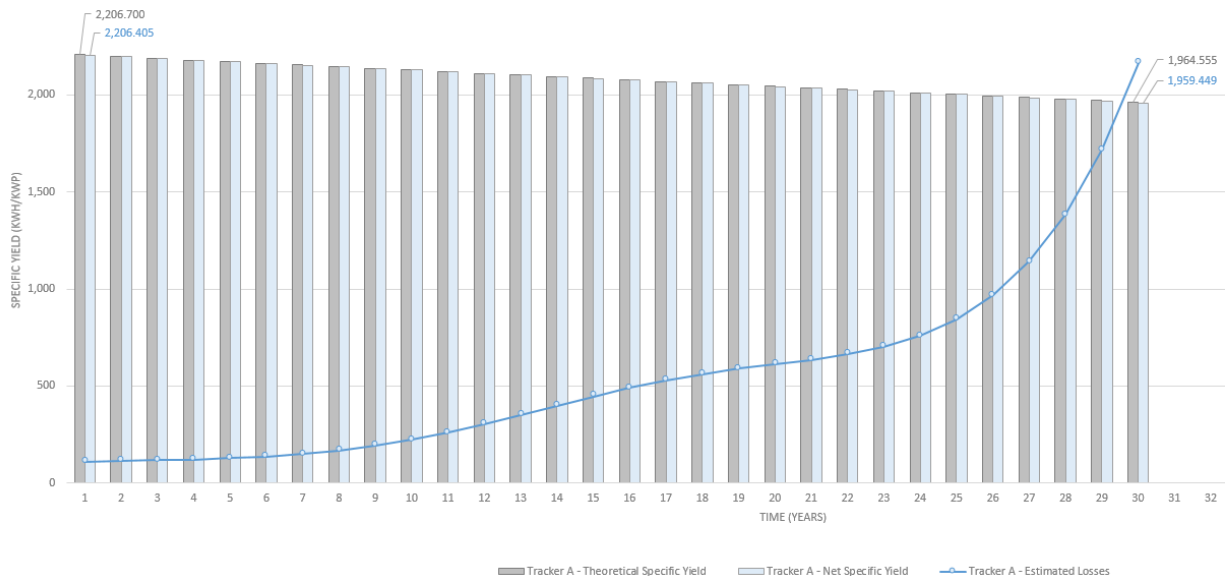
While there is a marked increase in the performance of Tracker B relative to Tracker A, the relative lifetime costs and economic metrics (LCOE and NPV) remain in favour of Tracker A.

**Table 14: Comparative results – GCR 0.285 with backtracking algorithm (Sensitivity 3)**

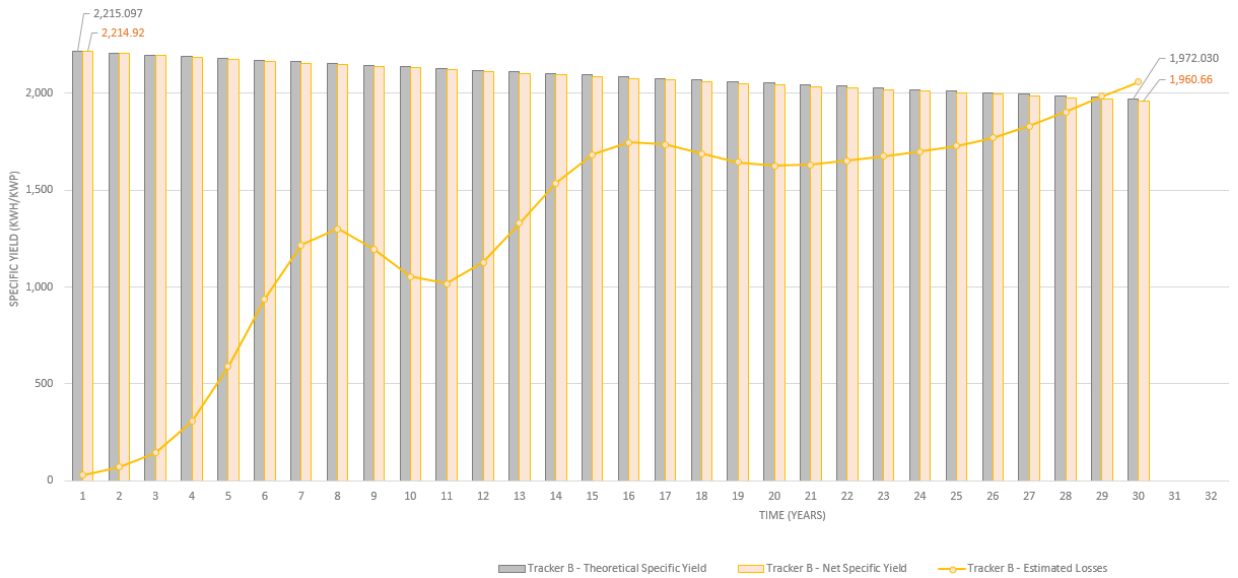
Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
<b>Headline results</b>				
Discounted Total Tracker Lifetime Cost (Absolute) (\$)	13,473,348.78	14,536,955.26	1,063,606.48	7.32%
Discounted Tracker Lifetime Cost (\$/MWp)	134,733.49	145,369.55	10,636.06	7.32%
LCOE (c\$/kWh)	3.45	3.48	0.03	0.89%
NPV PV Project(\$)	46,687,242.23	45,824,559.21	862,683.02	1.85%
<b>Tracker Energy Losses</b>				
Lifetime Energy Tracking Losses (Discounted)	0.04%	0.29%	0.25%	85.10%
<b>PV plant Generation</b>				
Net Lifetime Energy Generated (Revenue) (Discounted)	150,160,619.67	150,361,543.14	200,923.46	0.13%
Net Lifetime Energy Generated (MWh) (Discounted)	3,003,212.39	3,007,230.86	4,018.47	0.13%
Net Lifetime Energy Generated (MWh) (Undiscounted)	6,245,957.24	6,250,818.92	4,861.69	0.08%

As detailed within Section 5, similar trend graphs are realised for the Sensitivity 3 scenario. Graphs affected by the sensitivity analysis are presented below.

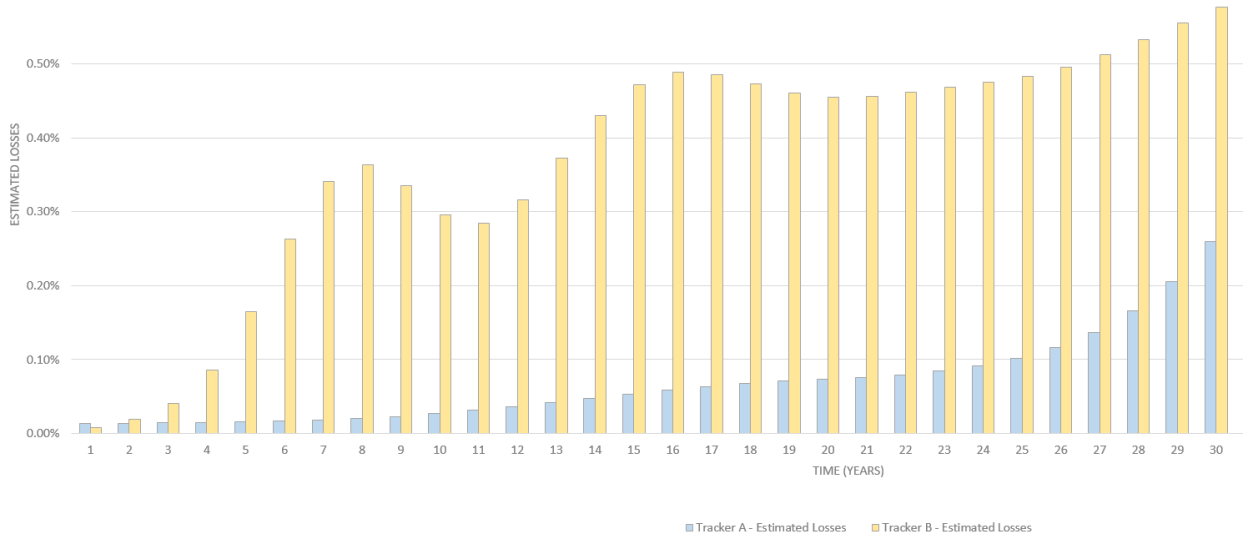
**Figure 26: PV Plant Lifetime Energy Generation – Tracker A – GCR 0.285 with backtracking**



**Figure 27: PV Plant Lifetime Energy Generation – Tracker B – GCR 0.285 with backtracking**



**Figure 28: Deviation from theoretical yield – GCR 0.285, 100 MWp with backtracking**



## 6 Conclusions

RINA notes the following key observations and conclusions with respect to this Case Study.

- RINA has been contracted by ARRAY to produce a strictly independent cost modelling tool (called PVTrax), which has been designed to provide a comparative lifetime cost assessment between the centralised ARRAY tracking technology and an equivalent decentralised tracking solution. The cost modelling tool has been based on assumptions produced by RINA from the perspective of an Independent Engineer. All inputs to the tool (such as component costs, inflation, discount rate, price of electricity, warranties, preventive maintenance schemes, estimated yield for each location, etc.) are variable inputs so the users are free to adapt the tool to consider different assumptions if these are considered more representative of the user's experience for the project of analysis.
- RINA and ARRAY have designed a Case Study based on a hypothetical 100 MWp PV plant located somewhere in California, USA. Technical characteristics associated with the Case Study have been chosen to be reasonably representative of the target market and to give a fair comparison between technologies, i.e. not favouring the ARRAY tracker (Tracker A) or the decentralised tracker (Tracker B).
- At the tracker level, discounted lifetime cost of ownership of Tracker B is significantly higher than Tracker A, with a relative difference of 7.32% (\$1,063,606.48 more expensive for the 100 MWp Case Study project, i.e. a lifetime cost difference of ~ 0.0106 \$/Wp). As summarised in Table 15, on a plant level NPV and LCOE basis, PVTrax shows that Tracker A presents advantages over Tracker B (within 0.9%-1.2% lower LCOE and within 1.9%-3.1% higher NPV). At the PV plant level, the lifetime cost of the PV plant (discounted) is 1.02% higher when using Tracker B.
- Main areas of difference between Tracker A and Tracker B are reduced OPEX for Tracker A, primarily due to reduction in failures experienced. The reduced failures modelled stem from the use of a smaller number of components of a centralised solution and because components with larger numbers of units per tracker (worm gears, gear racks and joints) are assumed to have lifetimes slightly above the PV plant lifetime. Tracker B has a wider variety of components with shorter lifetime (30 times more motors and controllers plus 30 times the addition of new components with shorter lifetime, i.e. batteries and battery chargers) affecting the variable OPEX significantly and tracker availability to a lesser extent. The reduced failure rates of Tracker A balance out the greater granularity of its centralised system and slightly lower yield (due to the lower ROM) leading to an improved availability and hence equal generation to Tracker B.
- As shown in Table 15, GCR and tracking algorithms do not have any influence in tracker cost, only on PV plant performance, and hence on LCOE and NPV.
- Numerous sensitivities can be analysed by users in PVTrax; RINA has analysed two scenarios where increased operational challenges are applied to Tracker B, which leads to improved performance for Tracker A, and another scenario with lower GCR, which slightly improves performance of Tracker B.
- Due to the high direct solar resource at the Case Study location, the diffuse irradiance algorithm does not introduce any significant benefit when compared to backtracking algorithm for any of the tracking technologies. Different algorithms would be expected to show greater variation on a site with greater diffuse irradiation, e.g. in Northern Europe.
- As shown in Table 15, both trackers perform better at lower GCR with equivalent improvement from GCR 0.4 to 0.285. Under normal operation (no failures) the yield analysis shows that Tracker B performs slightly better than Tracker A, especially at lower GCR, due to its wider

ROM ( $\pm 60$  degrees vs  $\pm 52$  degrees). However, as shown in Table 15, due to the lower availability of Tracker B along the lifetime of the PV plant, there is a narrow gap in net lifetime generation of the trackers (considering downtime due to component failures) with Tracker A performing slightly better at GCR 0.4 (0.16%, i.e. +4,752.73 MWh) and Tracker B performing slightly better at GCR 0.285 (0.13%, i.e. +4,018.47 MWh)

- Although there is a slight difference, the net lifetime yield of both tracking technologies is very similar with the deviation being within the yield energy uncertainty for all simulated scenarios of GCRs and tracking algorithms (see Table 15). Since net lifetime generation is within the same range for both tracking technologies, tracker lifetime OPEX is considered the main driver, in favour of Tracker A, for this economic comparative Case Study.
- While the conclusions derived from this assessment could be interpreted as applicable to sites with similar characteristics, it is noted that PV projects have a number of unique features and constraints (e.g. localised irradiance conditions, project design choices such as ground cover ratio, selected modules and inverter technologies, electrical configuration, tracking algorithms supported, labour costs, delivery costs, tracker component costs, cost of electricity, inflation, discount rate, project size, etc.) hence a project specific assessment is recommended in order to determine which tracking technology is more favourable.
- This report is intended to be considered in its entirety and specific statements quoted in isolation have not been endorsed for marketing purposes.

**Table 15: Summary of key economics and performance metrics for all simulated scenarios**

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
<b>Discounted Tracker Lifetime Cost (\$/MWh)</b>				
Same value for all cases of GCR and tracking algorithm <sup>11</sup>	134,733.49	145,369.55	10,636.06	7.32%
<b>LCOE (c\$/kWh)</b>				
GCR 0.4, BT <sup>12</sup>	3.56	3.60	0.04	1.18%
GCR 0.4, DT <sup>13</sup>	3.56	3.60	0.04	1.17%
GCR 0.285, BT	3.45	3.48	0.03	0.89%
GCR 0.285, DT	3.44	3.47	0.03	0.89%
<b>NPV PV Project(\$)</b>				
GCR 0.4, BT	41,775,764.89	40,474,521.95	1,301,242.93	3.11%
GCR 0.4, DT	41,941,912.18	40,660,434.87	1,281,477.31	3.06%
GCR 0.285, BT	46,687,242.23	45,824,559.21	862,683.02	1.85%
GCR 0.285, DT	46,939,543.85	46,066,790.00	872,753.85	1.86%
<b>Net Lifetime Energy Generated (MWh) (Undiscounted)</b>				
GCR 0.4, BT	6,041,748.62	6,028,759.88	12,988.74	0.21%

<sup>11</sup> Sensitivities 1 and 2 excluded

<sup>12</sup> BT: Backtracking algorithm

<sup>13</sup> DT: Diffuse tracking algorithm

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
GCR 0.4, DT	6,048,675.73	6,036,561.41	12,114.32	0.20%
GCR 0.285, BT	6,245,957.24	6,250,818.92	4,861.69	0.08%
GCR 0.285, DT	6,256,467.86	6,260,963.09	4,495.23	0.07%
<b>Net Lifetime Energy Generated (MWh) (Discounted)</b>				
GCR 0.4, BT	2,904,982.85	2,900,230.12	4,752.73	0.16%
GCR 0.4, DT	2,908,305.79	2,903,948.38	4,357.42	0.15%
GCR 0.285, BT	3,003,212.39	3,007,230.86	4,018.47	0.13%
GCR 0.285, DT	3,008,258.43	3,012,075.48	3,817.05	0.13%

## 7 Referenced documents

[1] **PV Tracker Lifetime Cost Assessment Methodology\_v1**, issued by RINA on 1<sup>st</sup> June 2020, which should be considered in conjunction with the results presented within this case study.

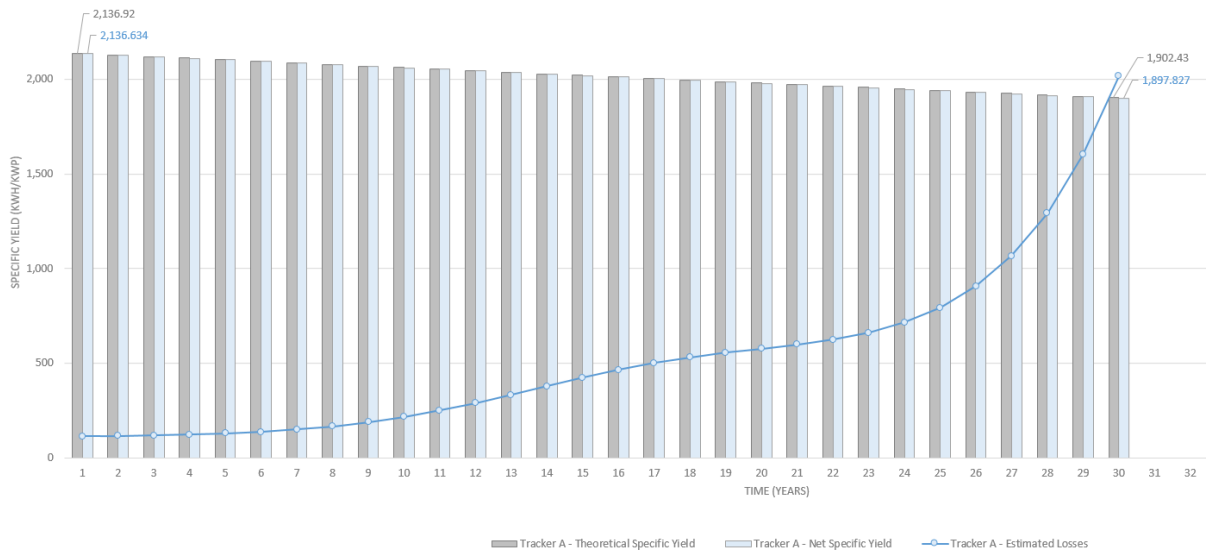
[2] **PVTrax – PV Tracker Lifetime Cost Assessment Model\_v1**, model developed and issued by RINA on 3<sup>rd</sup> June 2020. It has been used to perform the simulations presented in this comparative Case Study.

## Appendices

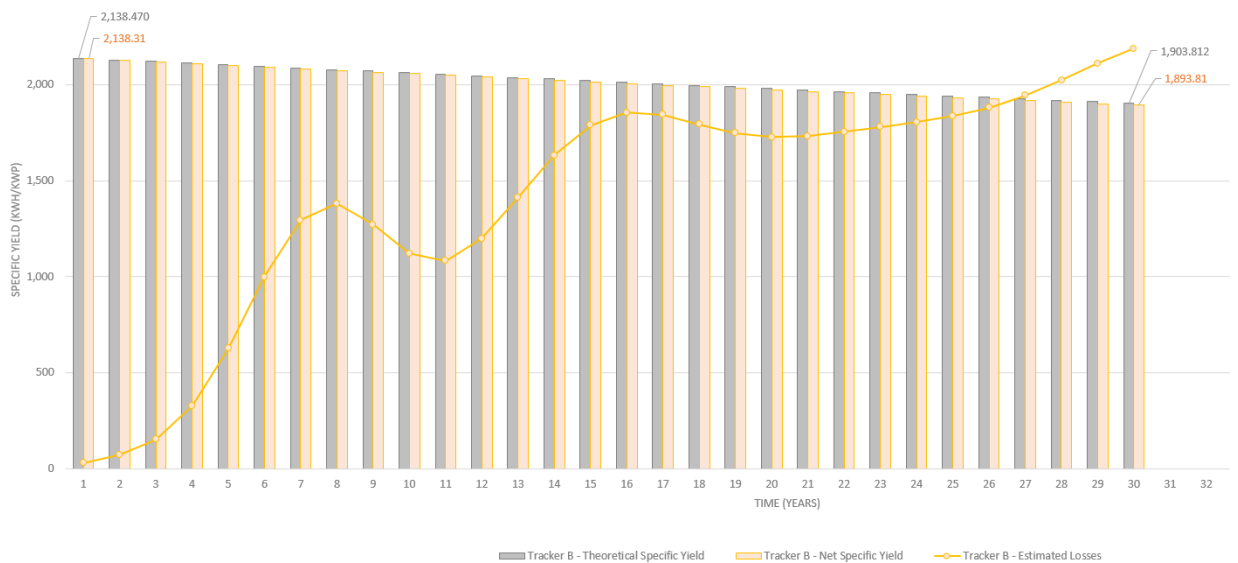
### A. Additional Model Results

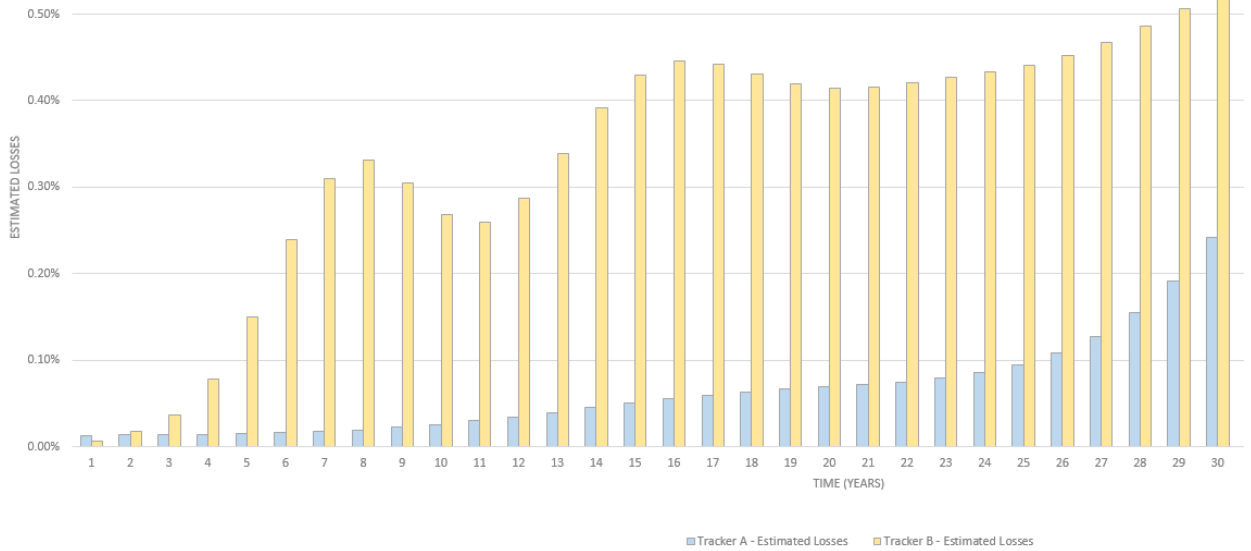
#### A.1. Diffuse tracking results – GCR 0.4, 100 MWp

**Figure 29: PV Plant Lifetime Energy Generation – Tracker A – GCR 0.4 with diffuse tracking**



**Figure 30: PV Plant Lifetime Energy Generation – Tracker B – GCR 0.4 with diffuse tracking**



**Figure 31: Deviation from theoretical yield – GCR 0.4, 100 MWp with diffuse tracking**


## A.2. Sensitivity 1: diffuse tracking results – GCR 0.4, 100 MWp

**Table 16: Comparative results – GCR 0.4 with diffuse tracking algorithm (Sensitivity 1)**

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
<b>Headline results</b>				
Discounted Total Tracker Lifetime Cost (Absolute) (\$)	13,584,876.55	14,760,010.80	1,175,134.25	7.96%
Discounted Tracker Lifetime Cost (\$/MWp)	135,848.77	147,600.11	11,751.34	7.96%
LCOE (c\$/kWh)	3.56	3.61	0.05	1.27%
NPV PV Project(\$)	41,823,247.58	40,437,379.33	1,385,868.25	3.31%
<b>Tracker OPEX</b>				
PV tracker OPEX - Fixed Costs (Discounted )	2,410.61	2,723.14	312.53	11.48%
PV tracker OPEX - Variable Costs (Discounted)	13,438.16	24,876.97	11,438.82	45.98%
PV tracker OPEX - Total Costs (Discounted)	15,848.77	27,600.11	11,751.34	42.58%
<b>PV plant Costs</b>				
Lifetime Cost of the PV plant (Absolute) (Discounted)	103,584,905.22	104,760,039.47	1,175,134.25	1.12%

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
Lifetime Cost of the PV plant (per MWp) (Discounted)	1,035,849.05	1,047,600.39	11,751.34	1.12%

Results are mostly the same with a very minor improvement in the generation, LCOE and NPV for Tracker B when compared with the backtracking algorithm simulation.

### A.3. Sensitivity 2: diffuse tracking results – GCR 0.4, 100 MWp

**Table 17: Comparative results – GCR 0.4 with diffuse tracking algorithm (Sensitivity 2)**

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
<b>Headline results</b>				
Discounted Total Tracker Lifetime Cost (Absolute) (\$)	13,980,884.83	15,812,710.87	1,831,826.04	11.58%
Discounted Tracker Lifetime Cost (\$/MWp)	139,808.85	158,127.11	18,318.26	11.58%
LCOE (c\$/kWh)	3.58	3.64	0.07	1.88%
NPV PV Project(\$)	41,434,376.13	39,384,679.26	2,049,696.87	4.95%
<b>Tracker OPEX</b>				
PV tracker OPEX - Fixed Costs (Discounted )	1,295.33	492.58	802.75	61.97%
PV tracker OPEX - Variable Costs (Discounted)	18,513.52	37,634.53	19,121.01	50.81%
PV tracker OPEX - Total Costs (Discounted)	19,808.85	38,127.11	18,318.26	48.05%
<b>PV plant Costs</b>				
Lifetime Cost of the PV plant (Absolute) (Discounted)	103,980,913.50	105,812,739.54	1,831,826.04	1.73%
Lifetime Cost of the PV plant (per MWp) (Discounted)	1,039,809.14	1,058,127.40	18,318.26	1.73%

Results are mostly the same with a very minor improvement in the generation, LCOE and NPV for Tracker B when compared with the backtracking algorithm simulation.

#### A.4. Sensitivity 3: diffuse tracking results – GCR 0.285, 100 MWp

**Table 18: Comparative results – GCR 0.285 with diffuse algorithm (Sensitivity 3)**

Comparative Metrics	Tracker A	Tracker B	Absolute Difference	Relative Difference
<b>Headline results</b>				
Discounted Total Tracker Lifetime Cost (Absolute) (\$)	13,473,348.78	14,536,955.26	1,063,606.48	7.32%
Discounted Tracker Lifetime Cost (\$/MWp)	134,733.49	145,369.55	10,636.06	7.32%
LCOE (c\$/kWh)	3.44	3.47	0.03	0.89%
NPV PV Project(\$)	46,939,543.85	46,066,790.00	872,753.85	1.86%
<b>Tracker Energy Losses</b>				
Lifetime Energy Tracking Losses (Discounted)	0.04%	0.29%	0.24%	85.01%
<b>PV plant Generation</b>				
Net Lifetime Energy Generated (Revenue) (Discounted)	150,412,921.29	150,603,773.93	190,852.63	0.13%
Net Lifetime Energy Generated (MWh) (Discounted)	3,008,258.43	3,012,075.48	3,817.05	0.13%
Net Lifetime Energy Generated (MWh) (Undiscounted)	6,256,467.86	6,260,963.09	4,495.23	0.07%

Results are mostly the same with a very minor improvement in the generation, LCOE and NPV for Tracker B when compared with the backtracking algorithm simulation.

## B. Project Feasibility Metrics

### B.1. Introduction to LCOE

LCOE is an economic metric used in energy projects to estimate the cost of producing energy with a certain technology and is typically expressed in \$/MWh. The cost of producing energy is intended to include any cost incurred at any time during the project's lifecycle, hence includes Capital Expenditures (CAPEX), Operational Expenditures (OPEX), and decommissioning costs. LCOE is therefore a useful metric that allows comparison of different energy generation technologies on a consistent basis. LCOE is particularly useful when assessing an energy project competing in an auction, as there is a strong relationship between the LCOE of a project and the price that auction bidders are likely to require to construct and operate a project in a particular location.

### B.2. Discount rate

Discount rates account for the time value of money. This can be defined as the compensation that investors require for receiving delayed reimbursements. Discount rate is an expression of the concept that money available to a business today is worth more than the same amount of money in the future; money immediately available can be invested for potential, whereas that same quantity in the future has lost the opportunity to yield any profit through investment in the intervening period.

Discount rates account for the risk of an investment. An investor considering an investment in a higher risk opportunity will require a greater rate of return to compensate for the risk being taken, expressed as a higher discount factor, while a low risk investment need only attract a low return, with a correspondingly lower discount factor.

### B.3. Net present value (NPV)

The NPV is a widely-employed economic measure used to assess both expenses and revenue streams together. The NPV is the addition of every year's cash flow discounted at the assumed discount rate, i.e., the discounted difference between the revenue and the cost streams. An energy project typically incurs CAPEX, OPEX and decommissioning expenditures, and obtains revenues through energy generation. Each of these sources of cash flow can be expressed in terms of a NPV.

### B.4. LCOE calculation

LCOE is typically calculated as follows:

$$LCOE = \frac{NPV_{Capex} + NPV_{Opex} + NPV_{Decom}}{\text{Discounted predicted generation}}$$

LCOE therefore takes account of the likely capital costs of a project, its operational costs, decommissioning costs, and through NPV the timing that each of these costs are incurred. RINA has observed that due to the impact of discounting, the following typically holds true when attempting to optimise LCOE:

- Generation is typically based on a yield study, so is often presented as a fixed value over the lifetime of the project, usually P50 or P90. As discounted generation is the denominator of the

LCOE calculation, any increase in yield leads to an equivalent decrease in LCoE, i.e. 1% more yield will lead to roughly 1% less LCoE.

- Renewable energy projects are capital intensive, and the vast majority of costs are incurred at the start of the project lifetime during construction, when the discount factor has limited impact on the NPV of the capital costs. As such, reductions in capital costs lead to a strong decrease in LCOE. As a very rough rule of thumb, a 1% reduction in CAPEX may lead to a 0.66% reduction in LCOE.
- Renewable energy projects do not have overly large operational costs, and these costs are incurred throughout the project lifetime, hence over time become more heavily discounted. As such, while OPEX is important, it has a more limited impact on LCOE – as a rough rule of thumb, a 1% reduction in CAPEX may lead to a 0.33% reduction in LCOE.
- Decommissioning costs typically have a limited impact on LCOE due to 25+ years of discounting.

## C. Supportive Literature on the Lifetime Cost Methodology

### C.1. Lifecycle maintenance and replacements

Further detail on the Case Study assumptions with regards to preventive and corrective maintenance for key components that form Tracker A and Tracker B are outlined below.

#### C.1.1. Drive motors

Tracker A uses an AC induction brushless motor to actuate tracker movements. Due to the nature of the motor, and the importance it plays over a high number of rows, ARRAY recommends undertaking maintenance of the motor and assess its condition in an annual basis.

Tracker B uses a small DC brushless motor for each row. While these motors may be subject to inspection during operation, their sealed natures mean it is typical operating practice for single row motors to be operated until failure. Due to the motors' sealed nature, the cost effectiveness of maintenance activities are typically limited until replacement is necessary.

With regards to corrective maintenance and lifetime failure rates estimation RINA's PV tracker lifetime cost Methodology differentiates between two types common drive motor technologies: brushless and brushed electrical motors. Both trackers A and B feature brushless drive motors which are considered more reliable and with a larger lifespan than brushed motors.

#### C.1.2. Transmission system

Both systems use a transmission system and gear box in order to rotate the torque tube.

One critical element of Tracker A are the gearboxes that transmits the rotational movement from the rotational driveline joints (via gear worms and rack gears) to each row. Based on documentation provided by ARRAY, these gear boxes are provided with the internal components immersed in synthetic lubricant and as such, no specific scheduled maintenance is expected to be required over the operational life. Similarly, for the Tracker B solution, the slew drive is sealed with no maintenance or additional lubrication required over the operational life. Tracker B motors are located in the proximity of the slew ring of each row. As such, less mechanical energy needs to be transmitted compared to Tracker A multi-row system presenting lower consumption, dimensions and unitary cost. Therefore, no preventive maintenance will be required for the transmission system of both tracking architectures.

With regards to corrective maintenance and lifetime failure rates estimation the Methodology identifies and model the key components comprising the transmission system for the common single-axis system available in the market:

- Connecting rods for push-pull drivelines systems;
- Worm gears, gear racks and joints for rotational drivelines;
- Slew drives or linear actuator for single row systems.

PVTrax considers three technologies (see below sorted in order from highest to lowest expected lifespan) when modelling the failure rates of these components:

- Connecting rods, gear racks and joints
- Worm gears and slew drives
- Linear actuators

### C.1.3. Bearings

Both architectures use bearings to support the rotational movement of the tracker. We note that both systems are assumed to have been designed to permit axial expansion and contraction. While the materials used to manufacture the bearing differ between the systems, both are considered highly reliable elements of the solution and are assumed to have employed suitably durable materials. Bearings are assumed to be replaced only in the event of a faulty component (damaged, broken or malfunctioned). No preventive maintenance of the bearings has been considered for any of the tracking's architectures.

PVTrax [2] models the bearings of both tracking technologies assuming equal lifetime failure profiles.

### C.1.4. Damping system

The two tracking architectures considered employ different sets of damping technologies, with the Tracker A system using a hydraulic solution and the single row tracker using a system with gas charged dampers. No preventive maintenance of the dampers has been considered for any of the tracking's architectures.

These dampers will require replacement in the event of failures (e.g. reduced hydraulic fluid viscosity for hydraulic solution or gas evacuation due to seal failure for gas charged solution). RINA has assumed that both damping systems are suitable for the application and as such would be subject to similar operational times before failure. It has been assumed that the dampers would be used for one full cycle each day and would be capable of 7,500 cycles (i.e. mean lifetime of about 20.5 years) prior to failure.

### C.1.5. Control systems

Motor controller and master controllers are modelled as industrial electronics, including their communication cards, whether wired or wireless. Motor controller in Tracker A is based on a commercial PLC device of a reputable manufacturer while Tracker B features a proprietary PCB based motor controller manufactured in house. Both of them have advantages and disadvantages. The use of commercial PLC from a reputable third party provider ensures reliability of the equipment (and it is more likely to find spares should ARRAY no longer trade) though may over time require upgrades of the control logic codes and firmware when new versions of the product are released. The use of proprietary PCB manufactured in house, on the contrary, may present higher failure rates until the product is well established and, spare wise, the owner would be limited to a single supplier. On the other hand, Tracker B manufacturer can optimise functionalities and costs in a more flexible manner.

With regards to communications and control logic, the Methodology assumes that system electronics and communication protocols and media are suitable for the application, that the design is in line with industry good practice and market standard and therefore, the correct operation of the system communications is not questioned.

Therefore, motor controllers, master controllers and data loggers are modelled as industrial "electronics" components and assumed to have equivalent operational lifetimes for both tracking architectures under comparison.

The mean lifetime assumed for the estimation of the corrective maintenance of the electronics (and modelled in PVTrax) assumes the use of established products and reputable manufactures (refer to Section 3)

#### C.1.6. Safety stowing system

In order to ensure the correct operation, annual functional tests of the system is a common preventive maintenance measure for tracking technologies with active safety stowing mechanisms.

No preventive maintenance of the specific electro mechanical components (apart from periodical calibration of the anemometers) are expected though. Only the cost due to corrective maintenance are quantified in the model (refer to Section 3.3)

The Methodology assumes that PV tracking technologies under comparison will comply with applicable regulations, codes and standards. Therefore, the risk of a structural failure occurring due to wind speed exceeding the tracker design limit is expected to be relatively low and acceptable for the project.

Damages caused by excessive wind events are generally covered by insurance. However, insurance policies often include a deductible or an excess value. This is the amount that a policyholder must bear before liability passes to the insurer. It varies with project, insurance provider and policyholder preference. Costs resulting from “minor” damages below the insurance deductible or excess affect OPEX.

Since the integrity of the PV tracking structure could be compromised if the stowing system (whether active or passive) fails under wind conditions above the tracker design limit, hypothetical additional costs (dependent on frequency, severity of the issues and insurance coverage) would affect, to a greater or lesser extent, the PV tracker OPEX. The Methodology provides guidance to evaluate the risk of occurrence of structural damage due to a failure in the stowing system with the sole purpose of providing additional insight to support stakeholders on the selection of the PV tracking technology and/or insurance policy (refer to Section 5.5 of RINA’s PV tracker lifetime cost Methodology Report [1] for more details)

Material cost and loss of generation (impact) in the event of a structural failure depends on numerous factors such as the severity and duration of the event (wind gusts exceeding the limit), wind direction, tilt of the tracker at the time of the incident, along with other project-specific parameters such as the cost of components, replacement time or labour cost.

For the purpose of the Case Study, failures on the components of the active safety stowing system are assumed to happen under wind speed below the tracker design limit and therefore, no extra cost due to potential damage has been considered.

#### C.1.7. Self-powered supply system: Batteries, battery charger and solar modules

The single row Tracker B solution uses batteries, typically Lithium-ion based, in order to power each row’s motor and control systems. Given each row operates independently, a functioning battery is required for normal operation.

In order to mitigate potential plant underperformance or hypothetical structural damage to the tracker, and associated damage to the modules (should the system need to engage the active safety stowing system in high wind conditions) ensuring the functional operation of the batteries is necessary.

Battery life is subject to a number of complex parameters including average state of charge, energy throughput (MWh released by the battery), and ambient temperatures. Operating a battery (i.e. absorbing/releasing energy) outside normal operating condition will reduce its state of health, thus reducing the usable energy capacity of the system over time and require early replacement. Additional project complexity arises from ensuring battery operation and associated warranty conditions have been considered for the project specific ambient conditions.

It is noted that over the project life, multiple battery replacements will be required for each row and should be considered within a project maintenance reserve account. We note that the extensive R&D (largely driven by electric vehicles) and the increased number of production facilities has greatly reduced prices for Lithium-ion based battery solutions. While further cost reductions can be assumed for future years, we note that there have been instances of price increases largely driven by commodity prices for key elements such as cobalt which bring a degree of uncertainty in future operational and replacement costs.

Tracker A drive motor and electronics are wired and parasitically powered from suitable low voltage switchboard, typically located in the inverter power stations, to supply power to auxiliary loads. Therefore, Tracker A does not require batteries.

In line with current practice, batteries, battery charger and solar modules are not expected to require preventive maintenance. Only corrective maintenance are considered in the Methodology. Lifetime expectancy and failure profiles of the of the lithium-ion batteries, battery charger and solar modules (refer to Section 3.3) have been modelled based on publicly available information, independent technical research and matched opinion of other PV solar independent engineers.

#### C.1.8. Cleaning and Mowing

With regards to mowing and cleaning, in order to capture and quantify the benefits of the most favourable tracker architecture, the PV tracker lifetime cost model [2] estimates only the deviation on mowing and cleaning costs and quantifies them as PV Tracker fixed OPEX (preventive) onto the most expensive architecture. In the Case Study, Tracker A, since it is a centralised architecture with disconnecting drivelines (and tractor based cleaning and mowing has been assumed) features slightly more expensive mowing and cleaning costs than Tracker B, and therefore, it is the only tracker that will incur associated cleaning and mowing preventive costs.

## C.2. PV tracker OPEX

**Table 19: List of Most Common Single-Axis Tracker OPEX Expenditure Units (EUs)**

Tracker OPEX Expenditure Unit (EU)	Explanation	Proposed subcategorization of the tracker OPEX parts
<b>Tracker Components</b>		
1 - Drive Motor (drive gear included)	<ul style="list-style-type: none"> <li>The Drive Motor is the fundamental part of the single-axis tracker which powers east-west rotation of the rows (centralised architecture) or row (decentralised architecture) by acting on the transmission system.</li> <li>Most of the single-axis trackers systems use either DC brushed, DC brushless or AC electric motors.</li> <li>Quantity and cost will depend on tracker technology. Although generally there is one Drive Motor per tracker, some manufacturers of centralised and decentralised architectures use two drive motors per tracker. The number of Drive Motors in decentralised architectures is higher than in centralised architectures (one/two per row vs one/two every 15-30 rows) since in multi-row systems the rows of a tracker are rotated by one or two Drive Motors via a driveline system which links all rows and transmits the rotation to each row (torque tubes).</li> <li>The per-unit cost of the Drive Motor in decentralised architectures is expected to be lower than in centralised architectures.</li> </ul>	The following subcategorization shall be followed when assessing the OPEX of the Drive Motor: <ul style="list-style-type: none"> <li>DC brushless or AC motor</li> <li>DC brushed motor</li> </ul> Quantity and cost will depend on the tracker architecture (centralised or distributed) For both systems, the drive gear (gear motor) is assumed to be included as part of the Drive Motor EU and, therefore, its associated cost should be estimated and accounted for in the lifetime cost assessment as part of the Drive Motor OPEX.
2 - Transmission Unit (gearboxes and other moving parts)	<ul style="list-style-type: none"> <li>Transmission units are the key moving parts of the tracker's transmission system. Regardless of architecture, the moving parts of the transmission system located at each row and responsible for rotating the row will be part of the transmission unit. The number of transmission units is equal to the number of rows. The technology of the transmission unit (e.g. slew drive, swing arm, gear rack, linear actuator) can vary with the tracker architecture and manufacturer.</li> </ul>	<u>Centralised systems</u> <ul style="list-style-type: none"> <li>Push-pull driveline <i>Connecting rods (swing arms)</i></li> <li>Rotating driveline <i>Worm gear</i></li> </ul>

Tracker OPEX Expenditure Unit (EU)	Explanation	Proposed subcategorization of the tracker OPEX parts
	<ul style="list-style-type: none"> <li>Apart from the moving parts present at each row, the drivelines in centralised systems are also moving parts of the tracker's transmission system. For the tracker OPEX estimate, under the assumption of a correct design and installation, only articulation joints in rotating articulating drivelines will be included as part of the transmission system.</li> </ul>	<ul style="list-style-type: none"> <li><i>Gear rack</i></li> <li><i>Articulating joints</i></li> <li><u>Distributed systems</u></li> <li>• <i>Linear actuator</i></li> <li>• <i>Slew drive</i></li> </ul>
3 - Bearing	<ul style="list-style-type: none"> <li>Bearings are required for the east-west rotation of the torque tubes, which are the rotating beams on which PV modules are mounted.</li> <li>There will be a bearing unit per each pole (supporting column) of the torque tube. The number of poles per torque tube, and therefore the number of bearing units, will vary with the tracker manufacturer and project design needs.</li> </ul>	<ul style="list-style-type: none"> <li>As defined in the Methodology, no subcategorization (differentiation) will be made for this tracker part, just quantification. Though these are similar in function, many bearings are significantly different in form and may have associated differences in unplanned maintenance.</li> <li>Unless otherwise stated by the tracker manufacturer, it shall be assumed that bearings do not require preventive maintenance (greaseless) and that the only difference across technologies will be the quantity of bearing units.</li> </ul>
4 - Harmonic Damper	<ul style="list-style-type: none"> <li>Typically, single-axis trackers have either one or two harmonic dampers at each end of each row installed at the outermost support columns of the torque tube.</li> </ul>	A subcategorization of expected lifetime of the damper (e.g. up to 10 years, from 10 to 20 years and

Tracker OPEX Expenditure Unit (EU)	Explanation	Proposed subcategorization of the tracker OPEX parts
	<ul style="list-style-type: none"> <li>The technology of the dampers may vary depending on the tracker manufacturer (e.g. hydraulic dampers, gas-charged dampers, hybrid hydraulic gas-charged).</li> <li>Lifetime of the damper could be given in lifetime cycles (compressed and extended) assuming they are operated within the expected designed load conditions.</li> <li>Damper failure can also lead to torque tube damage. The Methodology, does not account for any potential structure damage costs due to failures of tracker components.</li> </ul>	from 10 to 30 years) according to manufacturer information shall be considered when assessing the lifetime cost of this tracker part.
5 - Motor Controller	<ul style="list-style-type: none"> <li>The drive motor of each tracker, whether it is a single-row or a multi-row tracker, is controlled by a local electronic installed next to the tracker called a motor controller.</li> <li>Depending on the tracker architecture and manufacturer, there may be variations on the technology of the motor controller.</li> <li>Some motor controllers could be based on proprietary hardware (e.g. customised PCBs) or standard electronics existing in the control industry.</li> <li>Depending on the tracker manufacturer, the motor controller could operate independently (being in charge of driving the tracker motor according to the tracking algorithm and implement other functions such as stowing or communications with the SCADA system) or as a slave of one or more Master Controllers in charge of sending real-time set points and commands to them.</li> </ul> <p>It will be assumed each motor controller will be equipped with a communication card (wired or wireless) to communicate to the SCADA or to the Master Controller.</p>	As defined in the Methodology, no subcategorization (differentiation) will be made for this tracker part, just quantification.  In terms of communications, it will be presumed (under the assumption that the design and installation is done in line with good practices and industry standards) that wired and wireless electronics will have the same failure rates. This will also apply to the Master Controllers' communication interfaces or cards.
6 - Master Controller	<ul style="list-style-type: none"> <li>The Master Controller is an electronic device in charge of controlling several motor controllers. Depending on the tracker architecture a Master Controller could manage from a few to hundred motor controllers.</li> <li>It may or may not be present or depending on the tracker control architecture.</li> </ul>	In absence of manufacturer information, annual failure rates and average lifetime shall be

Tracker OPEX Expenditure Unit (EU)	Explanation	Proposed subcategorization of the tracker OPEX parts
	<ul style="list-style-type: none"> <li>• Communication between the motor and master controllers could be wired or wireless, depending on the communication technology used by the tracker manufacturer.</li> <li>• It is assumed that each Master Controller will be equipped with a communication card (wired or wireless) to communicate with SCADA and Motor Controllers.</li> </ul>	assumed for each technology based on public information.
7 - Power Supply	<ul style="list-style-type: none"> <li>• Depending on the way the trackers are powered, PV tracker can be classified as either:                             <ul style="list-style-type: none"> <li>– Self-powered trackers: A dedicated power system is installed to power one or more trackers (drive motor and electronics) typically composed of a solar module, a battery and a charger. The technology of the battery used, lifetime and capacity is expected to vary with the tracker manufacturer. Lithium-ion batteries are the most commonly used. This power supply architecture is generally used on single-row tracker architectures to minimise the power supply wiring. The OPEX shall include the lifetime costs of the solar module, battery charger and battery.</li> <li>– Parasitically-powered trackers: This category includes trackers either powered by DC systems wired directly from the PV array (more common in distributed architectures) or by an AC or DC auxiliary switchboard (more common in centralised architectures). The OPEX of the power supply for parasitically-powered trackers shall include the expected consumption (kWh/year) during the lifetime of the PV plant together with the cost of the electricity (variable inputs).</li> </ul> </li> </ul>	The following subcategorization shall be followed: <u>Self-powered trackers:</u> <ul style="list-style-type: none"> <li>• Solar module</li> <li>• Battery charger</li> <li>• Battery</li> </ul> <u>Parasitically powered</u> <ul style="list-style-type: none"> <li>• kWh/year</li> </ul>
8 - Wireless Repeater (where applicable)	Depending on factors such as technology and site topography, trackers with wireless communications may require the installation of repeaters to ensure communication between components (e.g. motor controllers and/or master controllers). The associated electronics of the wireless repeater together with the components of the power supply system used to feed the electronic shall be considered with estimating the tracker OPEX.	When applicable, the number of wireless repeaters should be quantified and the lifetime cost of the following parts (where applicable) should be estimated: <ul style="list-style-type: none"> <li>• Electronics</li> <li>• Solar module</li> </ul>

Tracker OPEX Expenditure Unit (EU)	Explanation	Proposed subcategorization of the tracker OPEX parts
	Different technologies may be used depending on the manufacturer (Zig-bee, industrial Wi-Fi, etc.)	<ul style="list-style-type: none"> <li>• Battery charger</li> <li>• Battery</li> </ul>
9 – Active Safety Stowing System	<ul style="list-style-type: none"> <li>• The integrity of the structure of some tracker technologies is guaranteed by means of an active safety stowing system which positions the tracker in a safe position under extreme wind speed conditions.</li> <li>• The key parts of an active safety stowing system are generally: anemometers, communication and control electronics and a secured power supply system.</li> <li>• Some active stowing systems are based on weather forecasts (external wind data source) and others on a combination of local wind measurement and wind forecasts.</li> <li>• Periodic preventive functional checks (fixed costs) are required to ensure the correct operation of the active safety stowing system.</li> <li>• PV plants are often equipped with weather stations including anemometers and communication electronics to store data integrated into the plant's SCADA system. When evaluating the lifetime cost only the OPEX associated with the additional parts required for the active safety stowing shall be included (e.g. the safety stowing system may require a wind sensor per tracker or per group of trackers). Typical weather station equipment and tracker controllers shall not be considered additional costs.</li> <li>• This tracker OPEX unit does not apply to trackers with passive safety stowing mechanisms.</li> </ul>	<p><u>Fixed costs</u></p> <ul style="list-style-type: none"> <li>• Preventive functional checks</li> <li>• Weather forecast data source (where applicable)</li> </ul> <p><u>Variable costs</u></p> <ul style="list-style-type: none"> <li>• Additional anemometers</li> <li>• Additional electronics</li> <li>• Additional controllers</li> </ul> <p>Additional power supply parts (e.g. UPS)</p>

Tracker OPEX Expenditure Unit (EU)	Explanation	Proposed subcategorization of the tracker OPEX parts
<b>PV plant preventive OPEX impacted by tracker architecture:14</b>		
10 – Mowing	<ul style="list-style-type: none"> <li>• Vegetation control (mowing grass) within the PV tracker area to avoid shading issues and proper operation and maintenance of the tracker is generally included in the scope of the O&amp;M contract.</li> <li>• For each tracker architecture, mowing fixed costs will be estimated. The difference mowing cost between tracker architectures (deviation) will be considered tracker preventive OPEX.</li> <li>• The tracker architecture could impact mowing time and therefore cost (e.g. presence of drivelines preventing the traffic of machinery)</li> <li>• Inter-row spacing may impact the type and/or dimensions of the machinery required. In the Methodology, it is assumed that the same mowing equipment will be used regardless.</li> <li>• The frequency of mowing will depend on specific site conditions and on the terms of the O&amp;M contract.</li> </ul>	For the estimate of the applicable preventive tracker OPEX, the following shall be assessed: <ul style="list-style-type: none"> <li>• Mowing frequency: mowing per year depending on the region and O&amp;M contract agreement.</li> </ul> For each tracker architecture: <ul style="list-style-type: none"> <li>• Mowing time: expected time to perform the mowing works considering any impact on the works due to the tracker architecture. The following subcategorization shall be followed: no drivelines, disconnecting drivelines and non-disconnecting drivelines.</li> <li>• Machinery cost</li> <li>• Labour cost</li> <li>• Difference mowing cost shall be applied to the tracker</li> </ul>

14 Other tracker preventive tasks not specifically related to the tracker OPEX units in Table 16, such as painting of rusty parts of the structure to prevent corrosion and assure the integrity of the structure and electrical bonding or torque inspections are assumed to be equivalent across technologies and therefore included in the scope of the O&M contract of the PV plant (non-tracker OPEX).

Tracker OPEX Expenditure Unit (EU)	Explanation	Proposed subcategorization of the tracker OPEX parts
		architecture leading to a more expensive mowing.
11 - Cleaning	<ul style="list-style-type: none"> <li>• Cleaning of the array to prevent underperformance is generally included in the scope of the O&amp;M contract.</li> <li>• For each tracker architecture, cleaning fixed costs will be estimated. The difference cleaning cost between tracker architectures (deviation) will be considered tracker preventive OPEX.</li> <li>• The tracker architecture could impact cleaning time and therefore costs (e.g. presence of drivelines preventing the traffic of machinery, gaps between modules)</li> <li>• When using traditional tractor-based cleaning, trackers with no drivelines may allow for a slightly cheaper cleaning (less time required). However, alternative technologies (e.g. robot-based cleaning) may be used depending on the project and manufacturer, which will impact the cost regardless the tracker architecture.</li> <li>• Inter-row spacing may impact the type and/or dimensions of the machinery required. In the Methodology, it is assumed that the same cleaning machinery will be used regardless.</li> <li>• Although cleaning could be done manually in some scenarios, it will be assumed that machinery will be used for cleaning.</li> <li>• The frequency of cleaning will depend on site specific conditions and on the terms of the O&amp;M contract.</li> </ul>	For the estimate of the applicable preventive tracker OPEX the following shall be assessed: <ul style="list-style-type: none"> <li>• Cleaning frequency: cleanings per year depending on the region and O&amp;M agreement.</li> </ul> For each tracker architecture: <ul style="list-style-type: none"> <li>• Cleaning time: expected time to perform the cleaning works considering any impact on the works due to the tracker architecture. It will depend on the cleaning solution used.</li> <li>• For tractor-based cleaning the following subcategorization shall be followed: no drivelines, disconnecting drivelines and non-disconnecting drivelines.</li> <li>• For robot-based cleaning the following subcategorization shall be followed: no gap between modules in the entire row, gap only in the centre of the row, more than one gap per row. Labour costs will increase with the number of gaps.</li> </ul>

Tracker OPEX Expenditure Unit (EU)	Explanation	Proposed subcategorization of the tracker OPEX parts
		<ul style="list-style-type: none"> <li>• Machinery/robot cost</li> <li>• Labour cost</li> <li>• Difference cleaning cost shall be applied to the tracker architecture leading to a more expensive mowing.</li> </ul>

### C.3. Tracker Unavailability and Yield Underperformance Estimation

Tracker components are expected to experience failures over the lifetime of the PV plant. In the event of a failure on any of the key parts required for the tracker to operate (i.e. drive motor, control electronics or power supply) the tracker will not follow the sun as expected resulting in underperformance or a loss of generation.

As defined in the Methodology, the underperformance due to PV tracker failures is directly proportional to the number of failures of the components responsible of the tracker movement, their associated replacement times and capacity impacted (granularity of the tracker). The lower granularity (as tracker B) the lower the impact of a tracker failure (less capacity affected). On the contrary, the higher the number of electro-mechanical components per tracker responsible for the tracker movement (as Tracker B) the higher the probability of a failure.

When a tracker is faulty, the associated yield underperformance is estimated on a yearly basis as per the procedure defined in the Methodology. As a brief summary, the percentage of time the tracker is available is quantified with the tracker producing as per the theoretical yearly energy yield while the percentage of time the tracker is unavailable is quantified with the tracker producing at a constrained energy yield. The constrained yield is an average weighted yield based on the probability of the tracker failing at different tracking angles throughout the year. For more details we recommend a thorough read of the Methodology [1].

Response time is the time between a tracker failure event and the replacement and commissioning of the faulty components. Response time is primarily driven by magnitude of impacted capacity since it is proportionally linked to loss of generation and cost of electricity (loss of revenue). Only generation hours (irradiance  $> 0 \text{ W/m}^2$ ) are considered in PVTrax when estimating tracker unavailability and associated PV plant underperformance. According to the solar resource of the Project location of the Case Study, the average daily hours with irradiance greater than  $0 \text{ W/m}^2$  is 12.4 hours. The Methodology assumes that components failures will happen independently (not simultaneously)

Due to the size of the Case Study PV project (100 MWp) we have assumed that the site will be attended, with spare parts available and therefore, with reasonable short response times.

OPEX wise, the model assumes that all failures (any component) will be addressed within each year period and the cost of the replacement is quantified and accounted (PV tracker OPEX)

However, performance wise, the model assumes that only failures of components related to the movement of the tracker (i.e. drive motors, motor controllers, batteries, battery charger, solar modules and key parts of the transmission system, i.e. as worm gear, gear rack, joints, connecting rods, slew drives, linear actuator) will impact on the availability of the tracker. Bearings and harmonic dampers will not generally prevent the tracker from operating and will be typically detected during preventive maintenance checks rather than via a tracking failure warning on the monitoring system. Additional components of the active safety system (anemometer, data logger, etc.) are assumed not to impact on the operation of the tracker (only effect on cost) since they do not prevent the tracker from operating normally.

The model assumes that the tracking algorithm is running on the motor controller, so a failure on the master controllers will not affect the operation of the tracker. Master controllers are principally responsible of sending automatic or manual set points (e.g. stowing, maintenance) and of gathering and sending information into the monitoring system.

In single-row systems, a failure of any of the above key components related to the movement of the tracker impacts on the whole tracker (1 row), generally a capacity of around 30 kWp. In the multi-row system is the same for non-disconnecting drivelines and for disconnecting drivelines in non-attended sites. In the multi-row system, for rotational disconnecting drivelines in attended sites (as in the Case Study), drive motors and motor controllers impact the whole tracker (generally a capacity of roughly 900 kWp) while a failure in parts of the transmission system do have different impacts. Worm gears and gear racks only impact one row (the row where they are) while the joints impact about half of the tracker (statistically calculated using probabilities of failures), assuming that site personnel will be able to disconnect the row in a reasonable prompt manner to allow the functioning part of the tracker to operate until the failure is addressed.

As an average, tracker downtime reduces yield performance about 33% for the solar resource of the Case Study. Response times are typically driven by revenue decrease over PV tracker downtime. Table 20 below table illustrates the response times assumed in the Case Study for the replacement of the tracker components responsible of the tracker availability. Indicative revenue losses<sup>15</sup> are shown only to help understanding the response time reasoning.

For Tracker B, since all components have the same impact over the tracker, equal response time (15 natural days) have been given to all components. Equivalent response time has been considered for the worm gear and gear rack transmission units of Tracker A, since they also impact only one row.

Driver motor and motor controllers in Tracker A are the critical components since a failure impacts the whole tracker (900 kWp approximately) with a response time of 5 natural days assumed. Since Tracker A has disconnecting drivelines (U-joints) and attended site assumed, a failure on the joints impacts probabilistically roughly half of the tracker capacity (15.5 rows = 465 Wp). Since joint replacement work is minor, response time of 5 natural days have been assumed, in line with drive motors and motor controllers.

**Table 20: Response time for the different tracker components of the Case Study**

Unit type	Tracker A Response Time	Tracker A Capacity impacted and Revenue loss	Tracker A Response Time	Tracker A Capacity impacted and Revenue loss
Drive motor	5 days <sup>16</sup> (62.1 hours)	900 kWp -\$332	15 days (186.4 hours)	30 kWp -\$33
Transmission unit - Worm gear	15 days (186.4 hours)	30 kWp -\$33	N/A	N/A
Transmission unit - Gear rack	15 days (186.4 hours)	30 kWp -\$33	N/A	N/A
Transmission unit - Joint	5 days (62.1 hours)	465 kWp -\$332	N/A	N/A
Transmission unit – Slew drive	N/A	N/A	15 days	30 kWp

<sup>15</sup> Estimated based on a performance ratio of 80%, averaged irradiance conditions during the faulty period of 450 W/m<sup>2</sup> (45% of standard test conditions) and energy price 0.05 \$/kWh.

<sup>16</sup> Calendar natural days and operating hours (irradiance > 0 W/m<sup>2</sup>) assumed for both technologies

Unit type	Tracker A Response Time	Tracker A Capacity impacted and Revenue loss	Tracker A Response Time	Tracker A Capacity impacted and Revenue loss
			(186.4 hours)	-\$33
Motor controller	5 days (62.1 hours)	900 kWp -\$332	15 days (186.4 hours)	30 kWp -\$33
Power supply – Battery	N/A	N/A	15 days (186.4 hours)	30 kWp -\$33
Power supply – Battery charger	N/A	N/A	15 days (186.4 hours)	30 kWp -\$33
Power supply – Solar module	N/A	N/A	15 days (186.4 hours)	30 kWp -\$33

Response time may depend on O&M contractual arrangements, project location (labour cost), etc. so it is expected to vary from project to project. However, we consider the response time assumed to be in line with industry good practice for an attended site with spare parts. It is reasonably short enough to prevent significant losses (especially on critical components of Tracker A) and to be realistically quick, in line with expectation although in some cases losses are not critical and would have wider response times (particularly for Tracker B).

Table 21 shows the yearly operating ratios (for a general year “j”) of the key tracking parts: drive motor, control electronics and power supply, where “T” are the total number of operating hours in a year ( $W > 0 \text{ W/m}^2$ ).

**Table 21: Operating time of tracking key OPEX parts for year “j”**

Tracker OPEX part (EU)	Number of failures	Replacement Time [hours]	Operating Ratio
Drive Motor (and drive gear)	$N_{1,j}$	$T_{1,j}$	$O_{1,j} = (T - N_{1,j} \times T_{1,j})/T$
Transmission units (Connecting rods (swing arms), Worm gear, Gear rack, Articulating joints, Linear actuator, Slew drive)	$N_{2,j}$	$T_{2,j}$	$O_{2,j} = (T - N_{2,j} \times T_{2,j})/T$
Control electronics <sup>17</sup> (Motor Controllers, Master Controllers, Wireless Repeaters)	$N_{3,j}$	$T_{3,j}$	$O_{3,j} = (T - N_{3,j} \times T_{3,j})/T$
Power supply (Solar modules, Battery chargers, Batteries)	$N_{4,j}$	$T_{4,j}$	$O_{4,j} = (T - N_{4,j} \times T_{4,j})/T$

<sup>17</sup> Only the control electronics components impacting on the operation of the tracker (movement) should be considered.

The tracking operating ratio ( $O_j$ ) and tracking non-operating ratio ( $\bar{O}_j$ ) for year “j” shall be calculated as follows:

$$O_j = O_{1,j} \times O_{2,j} \times O_{3,j} \times O_{4,j}$$

$$\bar{O}_j = (1 - O_j)$$

RINA’s PV tracker lifetime cost Methodology assumes that there will be a theoretical yield energy study ( $Y_{theoretical}$ ) already available for the project under evaluation (typically based on PVsyst or equivalent tool) which has accounted for all losses of the system<sup>18</sup> including system degradation over the lifetime of the PV plant and applicable tracking algorithm. The net lifetime energy generated ( $Y_{net}$ ) shall be calculated as follows:

$$Y_{net} = O_j \times Y_{theoretical} + \bar{O}_j \times Y_{tracking\_issues}$$

Where:

Variable	Units	Description
$O_j$	Dimensionless	Tracking operating ratio
$\bar{O}_j$	Dimensionless	Tracking non-operating ratio
$Y_{theoretical}$	kWh	PV plant theoretical Yield (tracking correctly)
$Y_{tracking\_issues}$	kWh	PV plant theoretical Yield with tracking issues (not tracking)

It will be assumed that a failure on any of the aforementioned tracking key parts will leave the tracker at a fixed tilt position. The underperformance due to tracking failure varies with the tilt at which the fault occurred (position), when the fault occurred, duration of the fault, and location of the site.

$Y_{tracking\_issues}$  is the theoretical yield of the PV plant in the scenario of the tracker remaining at a fixed position over the whole year and for each year over the lifetime of the PV plant, weighted based on the probability of the tracker being at each tilt once the fault occurred, considering only daylight time.

To estimate  $Y_{tracking\_issues}$  it will be assumed that in the event of a tracking failure the tracker will remain at any of the positions show in Table 22.<sup>19</sup> The average number of hours per day that the tracker will be at each position<sup>20</sup> (tilt duration) and their associated tilt ratios calculated over the above-mentioned daylight time (T) shall be extracted from the yield energy study of the project. For each position in Table 22, the theoretical yield shall be estimated assuming the tracker acting as a fixed tilt system.

18 Except for the losses due to tracking failures.

19 The tracking uncertainty is generally about  $\pm 5^\circ$ . A lower granularity (in steps of  $10^\circ$ ) could be used for the estimate of the yield underperformance if desired. However, for the purposes of the Methodology the proposed positions would be reasonable.

20 To calculate the number of hours associated to each angle, even intervals will be defined for each position (e.g. from  $-10^\circ$  to  $+10^\circ$  for tilt  $0^\circ$ , from  $+10^\circ$  to  $+30^\circ$  for tilt  $20^\circ$ , from  $+30^\circ$  to  $+50^\circ$  for tilt  $40^\circ$ , from  $+50^\circ$  to  $+MaxTilt$  for tilt  $+MaxTilt$ , and in the same way for the negative angles)

**Table 22: Weight of tracker's tilt angles and their associated fixed-tilt energy yields.**

Tilt Angle [ degrees]	Average Time per day at this position [hours] <sup>21</sup>	Tilt Ratio or Probability ( $p_i = t_i/T_{daytime}$ )	Theoretical Yield
- Maximum Tilt	$t_{-MaxTilt}$	$p_{-MaxTilt}$	$Y_{-Max tilt}$
- 40°	$t_{-40}$	$p_{-40}$	$Y_{-40}$
- 20°	$t_{-20}$	$p_{-20}$	$Y_{-20}$
0°	$h_0$	$p_0$	$Y_0$
+ 20°	$h_{+20}$	$p_{+20}$	$Y_{+20}$
+ 40°	$h_{+40}$	$p_{+40}$	$Y_{+40}$
+ Maximum Tilt	$h_{+MaxTilt}$	$p_{+MaxTilt}$	$Y_{+Max tilt}$

Where  $H$  is the estimated duration (daylight time) averaged over the whole year.

$$Y_{tracking\_issues} = \sum_{k=-MaxTilt}^{+MaxTilt} p_k \times Y_k$$

Where,  $k = \{-MaxTilt, -40, -20, 0, +20, +40, +MaxTilt\}$

Values in Table 22 are assumed to be known for each project (variable inputs). In absence of this information, an estimate could be modelled.

### C.3.1. Summary of the yield estimation assuming faulty trackers used in the Case Study

For each typical block (3150kWp), following the above procedure, the energy yield in the scenario of a fault were calculated for the different scenarios of GCRs and tracking algorithms (backtracking and diffuse tracking). Figures in tables below correspond to the yield generated by the typical electrical block chosen for the Case Study (3,150 kWp) which were escalated to 100 MWp (in PVTrax) when performing the comparative assessment.

**Table 23: Tracker A – Modelling Assumptions (GCR 0.4, Backtracking)**

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
-Maximum Tilt (east)	443	1.2	9.77%	4,138.49 MWh/year
- 40° (east)	639	1.8	14.09%	4,677.33 MWh/year
- 20° (east)	662	1.8	14.60%	5,380.87 MWh/year
0°	1033	2.8	22.78%	5,675.84 MWh/year
+ 20° (west)	664	1.8	14.64%	5,387.52 MWh/year
+ 40° (west)	661	1.8	14.58%	4,689.60 MWh/year

<sup>21</sup> Only during generation hours (daylight time)

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
+ Maximum Tilt (west)	433	1.2	9.55%	4,135.09 MWh/year
Total	4535	12.4	100.00%	Weighted Mean 5,008.84 MWh/year
Yield (tracking issues) escalated to 100 MWp			142,701.92 MWh/year	

#### 24: Tracker B – Modelling Assumptions (GCR 0.4, Backtracking)

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
-Maximum Tilt (east)	443	1.2	9.77%	3,728.18 MWh/year
- 40° (east)	639	1.8	14.09%	4,677.33 MWh/year
- 20° (east)	662	1.8	14.60%	5,380.87 MWh/year
0°	1033	2.8	22.78%	5,675.84 MWh/year
+ 20° (west)	664	1.8	14.64%	5,387.52 MWh/year
+ 40° (west)	661	1.8	14.58%	4,689.60 MWh/year
+ Maximum Tilt (west)	433	1.2	9.55%	3,717.58 MWh/year
Total	4535	12.4	100.00%	Weighted Mean 4,928.89 MWh/year
Yield (tracking issues) escalated to 100 MWp			140,424.30 MWh/year	

#### 25: Tracker A – Modelling Assumptions (GCR 0.4, Diffuse tracking)

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
-Maximum Tilt (east)	377	1.0	8.31%	4,138.49 MWh/year
- 40° (east)	624	1.7	13.76%	4,677.33 MWh/year
- 20° (east)	757	2.1	16.69%	5,380.87 MWh/year
0°	1038	2.8	22.89%	5,675.84 MWh/year
+ 20° (west)	703	1.9	15.50%	5,387.52 MWh/year
+ 40° (west)	658	1.8	14.51%	4,689.60 MWh/year
+ Maximum Tilt (west)	378	1.0	8.34%	4,135.09 MWh/year
Total	4535	12.4	100.00%	Weighted Mean 5,045.19 MWh/year
Yield (tracking issues) escalated to 100 MWp			143,737.72 MWh/year	

**26: Tracker B – Modelling Assumptions (GCR 0.4, Diffuse tracking)**

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
-Maximum Tilt (east)	376	1.0	8.29%	3,728.18 MWh/year
- 40° (east)	631	1.7	13.91%	4,677.33 MWh/year
- 20° (east)	763	2.1	16.82%	5,380.87 MWh/year
0°	1030	2.8	22.71%	5,675.84 MWh/year
+ 20° (west)	703	1.9	15.50%	5,387.52 MWh/year
+ 40° (west)	660	1.8	14.55%	4,689.60 MWh/year
+ Maximum Tilt (west)	372	1.0	8.20%	3,717.58 MWh/year
Total	4535	12.4	100.00%	Weighted Mean 4,976.94 MWh/year
Yield (tracking issues) escalated to 100 MWp				141,793.11 MWh/year

**27: Tracker A – Modelling Assumptions (GCR 0.285, Backtracking)**

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
-Maximum Tilt (east)	711	1.9	15.68%	4,374.00 MWh/year
- 40° (east)	540	1.5	11.91%	4,819.81 MWh/year
- 20° (east)	665	1.8	14.66%	5,486.68 MWh/year
0°	697	1.9	15.37%	5,675.84 MWh/year
+ 20° (west)	664	1.8	14.64%	5,493.94 MWh/year
+ 40° (west)	555	1.5	12.24%	4,824.45 MWh/year
+ Maximum Tilt (west)	703	1.9	15.50%	4,375.49 MWh/year
Total	4535	12.4	100.00%	Weighted Mean 5,009.66 MWh/year
Yield (tracking issues) escalated to 100 MWp				142,725.48 MWh/year

**28: Tracker B – Modelling Assumptions (GCR 0.285, Backtracking)**

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
-Maximum Tilt (east)	711	1.9	15.68%	4,025.07 MWh/year
- 40° (east)	540	1.5	11.91%	4,819.81 MWh/year
- 20° (east)	665	1.8	14.66%	5,486.68 MWh/year

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
0°	697	1.9	15.37%	5,675.84 MWh/year
+ 20° (west)	664	1.8	14.64%	5,493.94 MWh/year
+ 40° (west)	555	1.5	12.24%	4,824.45 MWh/year
+ Maximum Tilt (west)	703	1.9	15.50%	4,020.68 MWh/year
Total	4535	12.4	100.00%	Weighted Mean 4,899.96 MWh/year
Yield (tracking issues) escalated to 100 MWp			139,599.96 MWh/year	

### 29: Tracker A – Modelling Assumptions (GCR 0.285, Diffuse tracking)

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
-Maximum Tilt (east)	619	1.7	13.65%	4,374.00 MWh/year
- 40° (east)	543	1.5	11.97%	4,819.81 MWh/year
- 20° (east)	766	2.1	16.89%	5,486.68 MWh/year
0°	727	2.0	16.03%	5,675.84 MWh/year
+ 20° (west)	683	1.9	15.06%	5,493.94 MWh/year
+ 40° (west)	562	1.5	12.39%	4,824.45 MWh/year
+ Maximum Tilt (west)	635	1.7	14.00%	4,375.49 MWh/year
Total	4535	12.4	100.00%	Weighted Mean 5,048.72 MWh/year
Yield (tracking issues) escalated to 100 MWp			143,838.09 MWh/year	

### 30: Tracker B – Modelling Assumptions (GCR 0.285, Diffuse tracking)

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
-Maximum Tilt (east)	623	1.7	13.74%	4,025.07 MWh/year
- 40° (east)	539	1.5	11.89%	4,819.81 MWh/year
- 20° (east)	758	2.1	16.71%	5,486.68 MWh/year
0°	734	2.0	16.19%	5,675.84 MWh/year
+ 20° (west)	684	1.9	15.08%	5,493.94 MWh/year
+ 40° (west)	560	1.5	12.35%	4,824.45 MWh/year

Tilt Angle [ degrees]	Operation hours/year (GII>0)	Operation Av. Hours/day (GII>0)	Tilt Angle Probability	Theoretical Yield at each fixed tilt
+ Maximum Tilt (west)	637	1.7	14.05%	4,020.68 MWh/year
Total	4535	12.4	100.00%	Weighted Mean 4,950.65 MWh/year
Yield (tracking issues) escalated to 100 MWp				141,044.11 MWh/year

## D. Yield Assessment References

This section outlines the irradiation and yield study performed by RINA for the Case Study.

### D.1. Site Solar Resource

RINA's irradiation methodology has been applied to assess for the solar resource of the Case Study PV project. Global Horizontal Irradiation (GHI) values from a number of databases for comparison have been taken as shown in Table 31.

**Table 31: Annual GHI from various sources**

Data source	Period	Spatial resolution (km)	GHI (kWh/m <sup>2</sup> )	Difference from WM (%)
Meteonorm 7.2	1991-2010	8.0	1,925	-2.1%
SolarGIS	1999-2015	1.0	2,010	2.3%
3TIER	1997-2010	3.0	1,897	-3.5%
NSRDB	1998-2016	4.0	1,978	0.6%
Meteonorm 7.2	1991-2010	8.0	1,925	-2.1%
<b>Weighted Mean</b>			<b>1,966</b>	

The above selected irradiation value for the project (Weighted Mean or WM) has been weighted accounting for the number of years of data available of each source and inversely weighted based on their spatial resolution. Each parameter contributes 50% to the weighting. Along with the WM, the weighted deviation of each dataset relative to the WM value as well as the corresponding standard deviation has been calculated. Details on RINA's approach to assess long-term GHI is given in Section D.3.

The weighted mean value of **1,966 kWh/m<sup>2</sup>/year** has been selected for the energy yield assessment of the Case Study.

### D.2. Modelled system design and approach

There are a number of losses associated with the harvesting of sunlight for the generation of DC power and there are further losses in the conversion of DC power from the modules to the useful AC power that feeds to the grid, the cumulative loss of which defines the plant Performance Ratio (PR).

These specific losses are dependent on the system design and key plant components. For this plant, the modelled system design characteristics were based on the selected technology of the Case Study agreed between ARRAY and RINA. This includes site layout and component data sheets. Details are summarised in Table 34 to Table 36 in Section D.5.

Each individual loss has been modelled taking into account the information provided (and considered sufficient) and RINA proprietary models.

The following assumptions have been made in relation to the expected system design and installation:

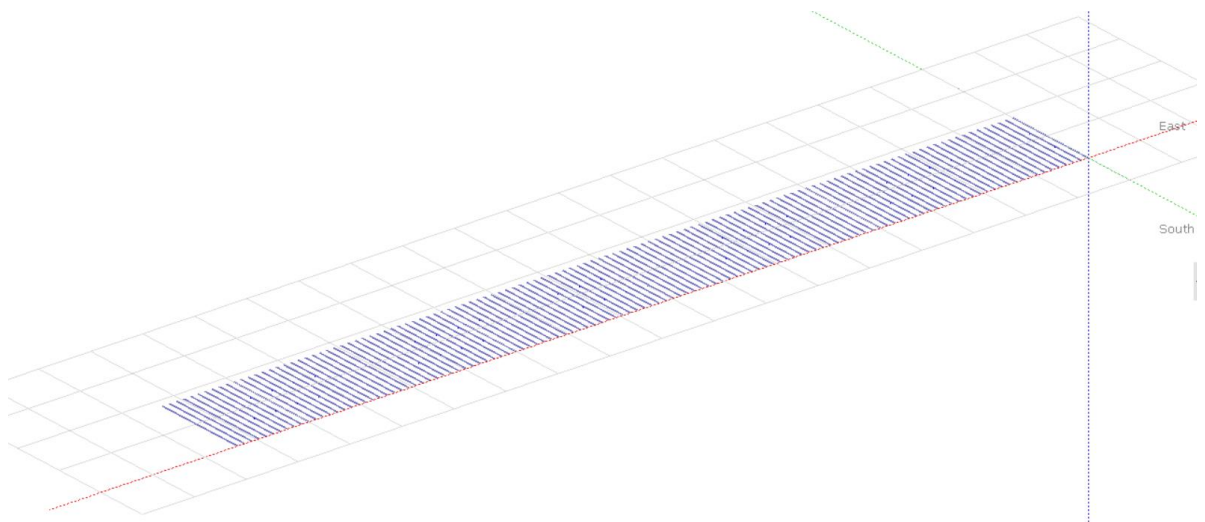
- Standard quality of the executed installation method

- General design and sizing criteria in line with quality standards. Quality standards include cable voltage drop limits, cabin heating and ventilation, control and protection settings etc.
- Final configuration of plant equipment to be completed using a standard approach
- For the purpose of this yield RINA has assumed a power factor of unity (PF=1) at the inverter level. There is likely to be a small amount of power factor required to overcome the inductive losses of the electrical transmission from the inverters to obtain unity at the connection point.

Where relevant PVsyst software (v6.79) is used, calculations are performed using hour-by-hour irradiance and ambient temperature values generated for the site.

The shading has been estimated according to the 3D model shown in Table 32. It has been assumed flat land with no shading objects. (e.g. overhead lines, trees and/or buildings). RINA has modelled this configuration accordingly in PVsyst.

**Figure 32: Simplified PVsyst near shading model**



**String sizing**

A typical block consisting of 10,800 modules has been selected for the analyses and the summary of the string configuration, power ratio, voltage and current compatibility of the string arrangement are detailed in Table 32.

**Table 32: System configuration**

Array size (kWp)	String configuration	No. of inverters	Power ratio (AC:DC)	Module	Max. voltage compatible	Max. current compatible
3,510	360 strings of 30 modules per SunGrow SG2500HV inverter	1	1:1.40	Canadian Solar CS6U32 5 MAX POWER	✓	✓

### D.3. Irradiation Database Information

RINA frequently reviews database updates available on the market and consider the datasets included in Table 33 to be the most applicable to a detailed irradiation analysis for this site.

**Table 33: Irradiation data sources**

Database	Description
Meteonorm 7.2	Meteonorm blends ground and satellite data for the period 1991-2010 from a database of approximately 1,325 weather stations with global radiation and temperature data. Where no radiation measurement is available nearer than 200 km (or 50 km in Europe) from the selected location, satellite information is used. If the nearest site is more than 30 km away (or 10 km in Europe), a mixture of ground and satellite information is used. In Europe the spatial resolution is between 2-3 km and 8 km for the rest of the world. The uncertainty of ground measurements ranges between 2% and 10%.
SolarGIS iMaps	This dataset is calculated from satellite observations made by Meteosat, GOES EAST and MTSAT satellite and MACC-II and GFS, CFSR atmospheric data. The data are spatially enhance to 1km resolution, the averaging periods are: 1994-2015 for Europe, Africa and the Middle East, 1999-2015 for Asia, 1999-2015 for Americas and 2007-2015 for the Pacific.
3TIER Solar Prospector Tool	Meteosat, GOES, GMS and MTSAT satellite visible imagery for cloudiness and other information to model the amount of solar radiation at the Earth's surface is used in this dataset. Available averaging period range from 1997-2010 in the Western Hemisphere, 1998-2010 in Europe and Africa to 1999-2010 in South Asia, Middle East, East Asia and Oceania. The spatial resolution is globally approximately 3km.
NSRDB 1998-2015	The National Solar Radiation Data Base 1961-1990 contains 30 years of solar radiation and supplementary meteorological data from 237 NWS sites in the U.S., plus sites in Guam and Puerto Rico. It was updated with a 1991-2010 database, which holds solar and meteorological data for 1,454 locations in the United States and its territories.  The current version of the NSRDB (v2.0.0) was developed using the Physical Solar Model (PSM), and offers users the latest available data (1998–2015). NSRDB comprises 30-minute solar and meteorological data for approximately 2 million 0.038-degree latitude by 0.038-degree longitude surface pixels (nominally 4 km <sup>2</sup> ). The area covered is bordered by longitudes 25°W on the East and 175°W on the West, and by latitudes - 20°S on the South and 60°N on the North.

### D.4. Irradiation Methodology

In order to determine the most accurate long-term GHI estimates, RINA continuously evaluates databases available on the market and data selection or weighting approaches. In this research, currently 38 locations spread over the global and in all relevant climate zones are used as benchmark locations. The benchmark data are predominantly taken from scientific radiation networks, which aim to provide data on climate change and model validation. Monthly and annual reference averages are based on a recent, period spanning several years.

Following RINA’s research, weighting methods have been found to provide more accurate long-term GHI estimates and typically outperform single databases, i.e. are superior to data selection. This can be explained by the nature of most databases, which is predominately model-reliant in terms of spatial resolution of information and sourcing. Furthermore, input data can be incomplete or not fully representative for a given location. Thus, location-specific estimates of single databases vary within modelling limits or can be biased. The most accurate single database evaluated so far comes globally with an uncertainty (RMSE) of the annual long-term GHI estimate of 2.6%. Weighting of various datasets appears to overcome partially this deficiency, with appropriate database selection being crucial in this context.

RINA has reviewed various approaches to combine datasets. Weighting of the databases on the basis of the number of years contained in each dataset and based on the inverse spatial resolution has been found globally most accurate with an uncertainty (RMSE) of the annual long-term GHI estimate of 2.2%. In this regard, spatial resolution and its inclusion in the weighting has shown increased significance when comparing the results obtained for locations binned into continental, coastal and small island sites.

For monthly long-term GHI estimates, similar results have been obtained with WM numbers being globally more accurate than single databases.

The results of RINA’s benchmarking effort have been published on 4th International Conference Energy & Meteorology in Bari, Italy in June 2017.

Egler, M.; Rusbridge, S.; Santos, C.: Solar Resource Databases vs Weighted Means – Results Of A Global Benchmarking Effort; 4th International Conference Energy Meteorology 2017; Bari, Italy; DOI: 10.13140/RG.2.2.36161.76646

## D.5. System Design

Specific losses are dependent on the system design and key plant components. For this Project, the modelled system design characteristics in Table 34 are based on the documents provided to RINA together with communications with and information provided by the Client.

**Table 34: Summary of modelling assumptions**

Description	Assumptions
DC installed capacity (kWp)	3,510.00
AC nominal capacity (kW; at 50°C)	2,500.00
AC maximum capacity (kW; at 25°C)	2,750.00
Power factor	1.00
Table configuration	1 module in portrait (1P)
Module tilt / Tracker range (°)	+/-52 degrees (Tracker A) +/-60 degrees (Tracker B)
Ground cover ratios	28.5%, 40%
Site inclination	Flat land assumed
Near shadings	No shading elements considered

The key equipment and string configuration is summarised in Table 35 and Table 36.

**Table 35: Equipment assumptions summary**

Equipment type	Assumptions				Source
	Manufacturer and model	Nominal power	Units	Quantity	
Modules	Canadian Solar CS6U325 MAX POWER	325	Wp	10,800	20190524 15h45 - Phase 3 - Q&A.xlsx
Inverter	SunGrow SG2500HV	2,500.0	kVA	1	20190524 15h45 - Phase 3 - Q&A.xlsx

**Table 36: Module string layout for PVsyst simulation**

Module String layout	Assumptions					Source
	Module model	Inverter model	No inverters	Modules per string	No strings per inverter	
String configuration	Canadian Solar CS6U325 MAX POWER	SunGrow SG2500 HV	1	30	360	20190524 15h45 - Phase 3 - Q&A.xlsx

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