RECOMMENDED PRACTICE

DNVGL-RP-0584 Edition March 2021

Design, development and operation of floating solar photovoltaic systems

DNV GL AS

FOREWORD

DNV GL recommended practices contain sound engineering practice and guidance.

Any comments may be sent by e-mail to *rules@dnvgl.com*

CHANGES – CURRENT

This is a new document.

Acknowledgements

This recommended practice has been developed based on results from a joint industry project (JIP). The work was performed by DNV GL and discussed in regular project meetings and workshops with individuals from the organisations participating in the JIP. They are hereby acknowledged for their significant, valuable and constructive inputs. The following organisations, listed in alphabetical order, participated to the JIP: Acciona, BayWa r.e, BlueC Engineering, Carpi Tech, Ciel & Terre International, CNR – Compagnie Nationale du Rhone, EDF - Électricité de France, EDP - Energias de Portugal, Equinor, Innosea - part of Aqualis Braemar LOC Group, Isigenere, JLD International, Mainstream Renewable Power, Makor Energy Solutions, Noria Energy, QuantSolar, RWE, Scatec, Seaflex, SolarMarine Energy, Statkraft, SunRise E&T Corporation, TNO, Total.

CONTENTS

SECTION 1 GENERAL

1.1 Introduction

The market for floating solar photovoltaic (FPV) systems is expanding rapidly. The successful, safe and reliable development of FPV projects requires clarity and wide-spread industrial agreement on requirements and best practices. Due to the lack of fit for purpose regulations and standards for FPV projects and FPV systems, there is an agreement among stakeholders that joint guidelines, practices and standards are necessary to realize the full potential of FPV and achieve large scale global deployment. This recommended practice (RP) aims to accelerate safe, sustainable and sound design, development, operation and decommissioning of FPV projects by presenting a comprehensive guideline and list of requirements and best practices.

This RP:

- focuses on methodology rather than on single technologies, to keep the RP as technology neutral as possible and provide functional requirements, recommendations and guidelines
- has a holistic system-level approach, including single key components as well as procedures and design considerations
- focuses on FPV projects in inland and near-shore water bodies, excluding offshore FPV.

This RP is written on the basis of the state-of-the-art knowledge and lessons learnt from operational FPV systems, while several topics included throughout the document require further research and clarification. Future updates of this RP are likely to expand the range of technology-specific recommendations and/or the range of applications included in the RP, as well as generally expanding the content and level of detail, following the FPV industry knowledge development and growth.

1.2 Objective

The objective of this RP is to provide a comprehensive set of requirements, recommendations and guidelines for design, development, operation and decommissioning of FPV systems. It aims to be valid and applicable in all major markets and geographic regions, for all defined applications within scope, from component level to system level, covering the entire life cycle. End users, developers, suppliers, investors, authorities and other stakeholders will be able to use this RP as their single all-encompassing guidance document for such systems, providing direct guidance or reference to other existing relevant guidelines and standards.

1.3 Scope

This RP focuses on FPV systems located in sheltered, in-land water bodies, while still being applicable for near-shore locations. A near-shore water body is intended as any water body, with salty, brackish or fresh water, geographically located close to a shoreline, in reasonably sheltered areas and with significant wave heights up to 2-3 m. Any offshore location, or location with harsher conditions, is considered explicitly out of scope of this RP. For these locations, this RP or parts of it may only be used as general guidance or as a reference.

The requirements, recommendations and guidelines included in this RP have been developed and written in accordance with recognized and agreed best practices and relevant standards, codes and guidelines, when present. Nonetheless, alternative methodologies, or alternative relevant standards, codes and guidelines, may be used in design, development and operation of FPV systems, when properly justified, documented and supported by sound engineering practices.

The requirements and guidelines listed in this document can never overrule any local, national and international applicable standards and regulations, which shall always be adhered to. The requirements and guidelines listed in this document are meant to provide guidance and to be used in absence of or in addition to such existing national standards and regulations.

1.4 Application

This RP focuses on the whole lifecycle of FPV systems, providing generic requirements that can be applied indistinctly to most available technological solutions. Furthermore, recommendations applying only to specific technologies are provided in the RP wherever necessary. The RP is based on existing and commercially available FPV components, but most of the functional requirements are expected to be applicable to future upcoming technological concepts as well.

The document is intended to guide the user in decision making, especially during the design phase of the project, with dedicated sections for the installation, operation and decommissioning phases. It is suggested to consult the whole document in early phase of the project, to understand the implication of site conditions and design choices on all phases of the project.

Applying this RP alone will not guarantee a fully secure FPV system: new technology can invalidate previous designs and using safe components will not automatically result in a safe system. Each project and site presents specific site conditions and challenges, which may not be fully foreseen and covered by this document. Specific assessments and sound engineering practices are vital in finding solutions and applying best practices to meet the requirements and guidelines listed in this document.

1.5 Relationship to other standardisation activities

The topics addressed in this RP are (partially) covered by a number of existing standards, documents and studies. This RP aims to collect the most relevant requirements, recommendations and guidelines of all these sources to present a guideline document for FPV projects with a system-level approach, but also including technology-specific aspects, where needed.

This RP is aligned with ongoing international effort towards standardization. Productive exchange of information has been established with relevant external stakeholders involved in standardization activities and research projects. In addition to existing codes, standards and rules, valuable information was gathered and reference was made to a number of existing documents and scientific papers, see Sec.13.

1.6 References

Table 1-1 lists DNV GL references used in this document.

Table 1-1 DNV GL references

Document code	*Title*
DNVGL-OS-A101	Safety principles and arrangements
DNVGL-OS-C101	Design of offshore steel structures
DNVGL-OS-E301	Position mooring
DNVGL-OS-E302	Offshore mooring chain
DNVGL-OS-E303	Offshore fibre ropes
DNVGL-OS-E304	Offshore mooring steel wire ropes
DNVGL-RP-0360	Subsea power cables in shallow water
DNVGL-RP-C203	Fatigue design of offshore steel structures
DNVGL-RP-C204	Structural design against accidental loads
DNVGL-RP-C205	Environmental conditions and environmental loads
DNVGL-RP-C212	Offshore soil mechanics and geotechnical engineering
DNVGL-RP-E305	Design, testing and analysis of offshore fibre ropes
DNVGL-ST-0119	Floating wind turbine structures
DNVGL-ST-0126	Support structures for wind turbine
DNVGL-ST-0359	Subsea power cables for wind power plants
DNVGL-ST-0437	Loads and site conditions for wind turbines
DNVGL-ST-C501	Composite components
DNVGL-ST-N001	Marine operations and marine warranty
DNVGL-ST-N002	Site specific assessment of mobile offshore units for marine warranty
RANA-WP-03-A	DNV GL white paper on PV degradation

Table 1-2 lists other references used in this document.

Table 1-2 Other references

Document code	*Title*
AODC 035	Code of Practice for the Safe Use of Electricity Underwater
API Spec 2F	Specification for Mooring Chain
API_RP_2SK	Design and Analysis of Station-keeping Systems for Floating Structures
AS 1170.2	Structural design actions - Wind actions
ASCE-7	Minimum Design Loads for Buildings and Other Structures

Document code	*Title*
ASTM D256	Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics
ASTM D635	Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position
ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D1693 - 15	Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics
ASTM D2990 - 17	Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics
ASTM D3801	Standard Test Method for Measuring the Comparative Burning Characteristics of Solid Plastics in a Vertical Position
ASTM D6110	Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics
ASTM E3010-15	Standard Practice for Installation, Commissioning, Operation, and Maintenance Process (ICOMP) of Photovoltaic Arrays
ASTM G154	Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials
ASTM G155	Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials
BS 3680	Measurement of liquid flow in open channels
BS 6349-1-2000	Maritime structures. Code of practice for general criteria
BS 6349-6	Maritime Structures – Part 6: Design of inshore moorings and floating structures
Directive 90/269/EEC	Directive 90/269/EEC on the manual handling of loads where
Directive 92/58/EEC	Directive 92/58/EEC - safety and/or health signs
Directive 94/25/EC	Directive 94/25/EC of the European Parliament and of the Council of 16 June 1994 on the approximation of the laws, regulations and administrative provisions of the Member States relating to recreational craft
Directive 2014/52/EU (EU-OSHA)	Directive 2014/52/EU of the European parliament and of the council
DMAC 02	In-water diver monitoring
DMAC 08	Thermal stress in relation to diving
DMAC 11	Provision of first aid and the training of divers, supervisors and members of dive teams in first aid
EU Directive 2016/425	Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC
EN 1990:2002	Basis of structural design
EN 1991	Actions on structures
EN 1993	Design of steel structures
EN 1997	Geotechnical design
EN 1999-1-1	Design of aluminium structures

Document code	*Title*
EN 10045-1	Metallic materials – Charpy impact test – Part 1: Test method
EN 10346	Continuously hot-dip coated steel flat products for cold forming. Technical delivery conditions
EN 13501	Fire classification of construction products and building elements, series
EN 16472:2014	Plastics. Method for artificial accelerated photoageing using medium pressure mercury vapour lamps
IEC 60068	Environmental testing
IEC 60076	Power transformers – Parts: 1, 2, 3, 4, 5, 7, 8, 10, 10-1, 11, 12, 13, 14 and 20
IEC 60183	Guidance for the selection of high-voltage A.C. cable systems
IEC 60364	Low-voltage electrical installations
IEC 60533	Electrical and electronic installations in ships - Electromagnetic compatibility (EMC) - Ships with a metallic hull
IEC 60529	Degrees of protection provided by enclosures (IP Code)
IEC 60584	Thermocouples
IEC 60707	Flammability of solid non-metallic materials when exposed to flame sources
IEC 60751	Industrial platinum resistance thermometers and platinum temperature sensors
IEC 60812	Failure modes and effects analysis (FMEA and FMECA)
IEC 61000-6-2 & IEC 61000-6-4	Electromagnetic compatibility (EMC) - Part 6-2 and Part 6-4: Generic standards – Immunity and emission standard for industrial environments
IEC 61215	Terrestrial photovoltaic (PV) modules – Design qualification and type approval
IEC 61400-1	Wind energy generation systems - Part 1: Design requirements
IEC 61400-12-1	Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines
IEC 61439	Low-voltage switchgear and controlgear assemblies
IEC 61537	Cable management - Cable tray systems and cable ladder systems
IEC 61701	Salt mist corrosion testing of photovoltaic (PV) modules
IEC 61724	Photovoltaic system performance
IEC TS 61724-3:2016	Photovoltaic system performance - Part 3: Energy evaluation method
IEC 61727	Photovoltaic (PV) systems - Characteristics of the utility interface
IEC 61730	Photovoltaic (PV) module safety qualification
IEC 61882	Hazard and operability studies (HAZOP studies)
IEC 61936	Power installations exceeding 1 kV a.c
IEC 62109	Safety of power converters for use in photovoltaic power systems
IEC 62116	Utility-interconnected photovoltaic inverters - Test procedure of islanding prevention measures
IEC 62208	Empty enclosures for low-voltage switchgear and controlgear assemblies - General requirements

Document code	*Title*
IEC 62305	Protection against lightning
IEC 62446	Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance
IEC 62477	Safety requirements for power electronic converter systems and equipment
IEC 62548	Photovoltaic (PV) arrays - Design requirements
IEC TS 62600-2	Marine energy - Wave, tidal and other water current converters - Part 2: Marine energy systems - Design requirements
IEC 62716	Ammonia corrosion testing of photovoltaic (PV) modules
IEC TS 62738	Ground-mounted photovoltaic power plants - Design guidelines and recommendations
IEC 62759	Photovoltaic (PV) modules - Transportation testing
IEC 62782	Photovoltaic (PV) modules - Cyclic (dynamic) mechanical load testing
IEC 62790	Junction boxes for photovoltaic modules - Safety requirements and tests
IEC 62804	Test methods for the detection of Potential Induced Degradation
IEC 62852	Connectors for DC-application in photovoltaic systems - Safety requirements and tests
IEC 62920	Photovoltaic power generating systems - EMC requirements and test methods for power conversion equipment
IEC 62930	Electric cables for photovoltaic systems with a voltage rating of 1,5 kV DC
IEC 63026	Submarine power cables with extruded insulation and their accessories for rated voltages from 6 kV (Um = 7,2 kV) up to 60 kV (Um = 72,5 kV) - Test methods and requirements
IEEE 1547	Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
IEEE 80	Guide for Safety in AC Substation Grounding
IMCA HSSE 021	Risk assessment
IMCA D 010	High voltage training: A syllabus for training offshore workers involved with high voltage equipment
IMCA D 018 Rev.1	Code of Practice for the initial and periodic examination, testing and certification of diving plant and equipment
IMCA D 021 Rev.1	Diving in contaminated waters
IMCA D 023	Diving Equipment Systems Inspection Guidance Note for Surface orientated (air) diving systems
IMCA D 045	Code of practice for the safe use of electricity underwater
IMCA D 039	FMEA for diving systems including aspects of life support for divers
IMCA D 040	Design for mobile/portable surface supplied systems
INDS28	Health & safety executive on floating fish farm installations
ISO 179-1:2010	Plastics - Determination of Charpy impact properties - Part 1: Non-instrumented impact test
ISO 180	Plastics – Determination of Izod impact strength
ISO 527-1:2019	Plastics - Determination of tensile properties

Document code	*Title*
ISO 868	Plastics and ebonite — Determination of indentation hardness by means of a durometer (Shore hardness)
ISO 1070	Hydrometry — Slope-area method
ISO 4892-2: 2013	Plastics - Methods of exposure to laboratory light sources – Part 2: Xenon-arc lamps
ISO 4892-3: 2016	Plastics — Methods of exposure to laboratory light sources — Part 3: Fluorescent UV lamps
ISO 5667-4:2016	Water quality — Sampling — Part 4: Guidance on sampling from lakes, natural and man-made
ISO 5667-6:2014	Water quality — Sampling — Part 6: Guidance on sampling of rivers and streams
ISO 9060	Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation
ISO 9772	Cellular plastics — Determination of horizontal burning characteristics of small specimens subjected to a small flame
ISO 9846	Solar energy — Calibration of a pyranometer using a pyrheliometer
ISO 9773	Plastics — Determination of burning behaviour of thin flexible vertical specimens in contact with a small-flame ignition source
ISO 11357-6	Plastics — Differential scanning calorimetry (DSC) — Part 6: Determination of oxidation induction time (isothermal OIT) and oxidation induction temperature (dynamic OIT)
ISO 17776	Petroleum and natural gas industries — Offshore production installations — Major accident hazard management during the design of new installations
ISO 19901-1	Petroleum and natural gas industries — Specific requirements for offshore structures — Part 1: Metocean design and operating considerations
ISO 19901-6	Petroleum and natural gas industries — Specific requirements for offshore structures — Part 6: Marine operations
ISO 19901-7	Station keeping systems for floating offshore structures and mobile offshore units
ISO 19901-8	Petroleum and natural gas industries — Specific requirements for offshore structures — Part 8: Marine soil investigations
ISO 19901-10	Petroleum and natural gas industries — Specific requirements for offshore structures — Part 10: Marine geophysical investigations
ISO 19906	Petroleum and natural gas industries — Arctic offshore structures
ISO 12944	Corrosion protection of steel structures by protective paint systems
ISO 21650:2007	Actions from waves and currents on coastal structures
ISO 22088	Plastics — Determination of resistance to environmental stress cracking (ESC) is applicable to wider range of plastics
ISO/TC147/SC 6	Technical Committee on Water Quality, Sub-committee on General sampling methods
JIS C 8955 (2017)	Load design guide on structures for photovoltaic array
NEPA	US National Environmental Policy Act
NORSOK N-003	Actions and action effects
NORSOK N-004	Design of steel structures

Document code	*Title*
NS 9415	Marine fish farms - Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation
OSHA	Occupational safety and health administration
OSIG (2014)	Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Off-shore Renewable Energy Developments
PIANC	Suite of guidelines and recommendations
UL 94	Tests for Flammability of Plastic Materials for Parts in Devices and Appliances
WMO-No.686	Manual on operational methods for the measurement of sediment transport

1.7 Definitions and abbreviations

1.7.1 Definition of verbal forms

The verbal forms defined in Table 1-3 are used in this document.

Table 1-3 Verbal forms

Verbal form	*Definition*
shall	verbal form used to indicate requirements strictly to be followed in order to conform to the document
should	verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others
may	verbal form used to indicate a course of action permissible within the limits of the document

1.7.2 Definition of terms

The terms defined in Table 1-4 are used in this document.

Table 1-4 Definitions of terms

Term	*Definition*
3-T	the load bearing capability of synthetic-yarn materials is referred to as 3-T (triple T) since it depends on the combination of the critical parameters 'tension', 'temperature' and 'time'. As the criticality of each parameter depends on the other two critical parameters, all three maybe seen as a single, three-dimensional, critical parameter called 3-T
aperture ratio	the ratio of focal length to effective aperture diameter. For PV systems this is the PV arrays height over ground and length of surface with PV modules
absorption coefficient	how much the light which is observed by the PV module is absorbed
buoyancy	hydrostatic force acting on a partially or fully submerged body, equal in magnitude to the volume of water displaced by the object
biofouling	the accumulation of microorganisms, plants, algae, or small animals on wetted surfaces
capacity check	check of the utilization factor to find out what portion of the resistance has been met

Term	*Definition*
change-in-length performance	length and dynamic stiffness of the fibre rope/tether as function of loading sequence and time
characteristic load	reference value of a load to be used in the determination of the design load. The characteristic load is normally based upon a defined quantile in the upper tail of the distribution function for load
characteristic load effect	reference value of a load effect to be used in the determination of the design load effect. The characteristic load effect is normally based upon a defined quantile in the upper tail of the distribution function for load effect
characteristic value	representative value of a load variable or a resistance variable. For a load variable, it is a high but measurable value with a prescribed probability of not being unfavourably exceeded during some reference period. For a resistance variable it is a low but measurable value with a prescribed probability of being favourably exceeded
collinear environment	wind, waves and current acting from the same direction
creep	an irreversible change in material strain (extension/stretching) over time under load
data coverage	data which has been subjected to filtering processes and is found to be representative and appropriate for analysis purposes
deep water	waters characterized by water depth greater than half of the wavelength of the predominant wave
downside risk	the probability of a low production year occurring during the project's lifetime. The downside risk can be represented in terms of probability of exceedance, which is the probability that the energy production will be in excess of a certain amount, expressed as a percentage of the long-term average estimate
element	individual float or interconnection which forms part of an FPV
energy yield assessment	modelling of the average yearly expected energy production of an FPV system over the lifetime of the project
engineering judgement	a process by which a design, installation, operation/maintenance or safety problem is systematically evaluated
environmental actions	any external phenomenon (eg. wind, waves, current) which may cause a load on a structure
electrical layout	the design of the electrical system of the FPV project
electrical component	a component in the electrical layout
expected value	the expected value from a probability distributions, also known as the mean value
fatigue analysis	analysis to determine the stress ranges due to fatigue loads
fatigue damage	ratio of number of applied load cycles and the corresponding number of cycles to failure at a constant stress range
fatigue life	number of stress cycles at a particular magnitude required to cause fatigue failure of the component
fatigue limit	fatigue strength under constant amplitude loading corresponding to a high number of cycles large enough to be considered as infinite by a design code
fatigue resistance	structural detail's resistance against fatigue actions in terms of SN curve or crack propagation properties

Term	*Definition*
fatigue strength	magnitude of stress range leading to a particular fatigue life
fetch length	the horizontal length over an ocean or a lake surface which wave-generating winds blows in an essentially constant direction
free board	the distance between the waterline and surface of the float
fibre rope segment	fibre rope with terminations, excluding termination hardware
float	an individual floating assembly on a water body with a defined function
floating structure	the collection of floats on a water body excluding electrical components that form part of a solar PV installation
FPV array	the ensemble of floats and components, part of a solar PV installation on a water body used for collecting, converting and transmitting energy and includes PV modules and supporting structure. A floating structure can include balance of system (inverter and transformer) but excludes station keeping
FPV project	the process entailing engineering, design, installation, commissioning, O&M and decommissioning of an FPV system
FPV system	the ensemble of components part of a solar PV installation on a water body used for collecting, converting and transmitting energy into a POC (e.g. grid or load), including PV modules, supporting structure, station keeping, balance of system up to the POC
grid interconnection point	point where the FPV plant is connected with the electricity grid
gust	peak of a time series of wind speed, averaged over an interval of three (3) seconds
inclinometer	an instrument used for measuring angles of slope, elevation, or depression of an object with respect to gravity's direction
limit state	state beyond which the structure no longer fulfils the relevant design criteria
manufacturer	company or entity which makes finished components or products from raw materials or smaller components and sell it to customers/buyers
marine growth	soft (bacteria, algae, sponges, sea quirts and hydroids) and hard fouling (goose, barnacles, mussels and tubeworms)
maximum power point tracker	algorithm included in inverters used for extracting maximum available power from PV module under certain conditions
meteorological measurement station	setup of measurement sensors in one unit for the measurement of meteorological parameters for input in the energy model
microclimatic	climatic conditions in a small area where conditions are dependence on factors such as temperature, humidity, wind and turbulence, dew, frost, heat balance, and evaporation
modbus	a communication protocol developed by Modicon systems. In simple terms, it is a method used for transmitting information over serial lines between electronic devices
modelling bias	discrepancy between the nameplate rating and the simulation software modelled power rating in the PV module PAN file
multibody float	floating structure composed by multiple floats with internal interconnections between them
nameplate bias	the difference between how much power the PV module is actually producing compared to its nameplate power rating

Term	*Definition*
near shore	any location, with salty, brackish or fresh water, geographically located close to a shore line, in reasonably sheltered areas, with water depth up to 50 m and with significant wave height up to 2 m-3 m
offshore	any location, in unsheltered water, geographically located far from the shore line, with water depth greater than 50 m and/or with significant wave height greater than 2 m-3 m
OND file	file containing the specifications for an inverter
long-term	duration of more than 12 years
PAN file	file containing the specifications for a PV module
peak period	wave period determined by the inverse of the frequency at which a wave energy spectrum has its maximum value
permit	official document authorizing someone to do or build something
photovoltaic cable	cabling on the DC side of the inverter
power derating	the operation of a unit at less than its rated maximum capability (at a given time)
PV module	assembly of photovoltaic cells mounted in a framework for installation
pyranometer	Pyranometers measure global irradiance, the amount of solar energy per unit area per unit time incident on a surface of specific orientation emanating from a hemispherical field of view
redundancy	Ability of a component or system to maintain its function when one failure has occurred. Redundancy may be achieved, for instance, by installation of multiple components, systems or alternative means of performing a function
return period	estimated average time until the next occurrence of a defined event
righting moment	the tendency for a floating body to resist inclination and return to equilibrium
satellite data	meteorological data interpreted from satellite imagery
sea state	the wave conditions present for a certain duration, e.g. 3 hours, mainly defined by a characteristic wave height and a characteristic wave period
significant wave height	average height (trough to crest) of the highest one-third waves in the indicated time period
single-body float	single floating structure without internal interconnections to multiple floats
soiling profile	soiling profile is a percentage soiling loss typically defined per month in the energy simulation software
solar monitoring station	same definition as 'meteorological measurement station'
squall	sudden violent gust of wind, or a localized storm
station-keeping system	system capable of limiting the excursions of a floating structure within prescribed limits. In FPV installation this is typical composed of mooring and anchoring system
supporting structure	structural members providing mechanical support for the electrical equipment that forms part of a solar PV installation
swell	long waves which have propagated over a long distance, generated by storms far away out in the ocean
temporary mooring	mooring system applied in a time-restricted period during building and installation. Can include components that will be part of the final mooring system

Term	*Definition*
wave direction	main direction of propagation of a wave component
wave frequency loads	first order wave loads in the frequency range of the incoming waves
wind sea	waves generated by the local wind
wind shear	difference in wind speed or direction over a relatively short distance in the atmosphere
zero-up-crossing wave	wave that crosses the average water level in an upward direction

1.7.3 Abbreviations

The abbreviations described in Table 1-5 are used in this document.

Table 1-5 Abbreviations

Abbreviation	*Meaning*
AC	alternating current
ALS	accidental limit states
AODC	Association of Offshore Diving Contractors
BEM	boundary element model
BoS	balance of system
CAPEX	capital expenditures
CCTV	closed-circuit television
CPR	cardiopulmonary resuscitation
CU	cost unit (e.g. €, $)
CFD	computational fluid dynamics
DAF	dynamic amplification factor
DC	direct current
DFF	design fatigue factor
DHI	diffuse horizontal irradiation
DMAC	Diving Medical Advisory Committee
DSC	differential scanning calorimetry
EA	energy assessment
EIA	environmental impact assessment
ESIA	environmental and social impact assessment
EMC	electromagnetic compatibility
EN	European Standard
EPA	energy production assessment

Abbreviation	*Meaning*
EPC	engineering, procurement and construction
ESS	extreme sea state
EWH	extreme wave height
EYA	energy yield assessment
FAT	factory acceptance test
FLS	fatigue limit state
FMEA	failure mode and effects analysis
FTD	flash test data
FPV	floating photovoltaic
GCR	ground cover ratio
GHI	global horizontal irradiation
GTI	global tilted irradiation
HAT	highest astronomical tide
HAZID	hazard identification
HAZOP	hazard and operability study
HDPE	high density polyethylene
HIL	highest impounded level
HMPE	high modulus polyethylene (also UHMWPE)
HRT	highest recorded tide
HSE	health, safety and environment
HV	high voltage (above 69,000 Volt)
IAM	incidence angle modifier
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IMCA	International Marine Contractors Association
Imp	current at maximum power
Isc	short circuit current
IT	isolation terra
ISO	International Organization for Standardization
JIP	joint industry project
LIL	lowest impounded level
LAT	lowest astronomical tide
LCA	life cycle assessment

Abbreviation	*Meaning*
LCOE	levelized cost of energy
LCP	liquid-crystal polymer
LID	light-induced degradation
LRT	lowest recorded tide
LV	low voltage (below 1000 Volt AC and 1500 Volt DC)
MBL	minimum breaking load
MCP	measure correlate predict
MHWS	mean high water springs
MLWS	mean low water springs
MV	medium voltage (above 1000 volt AC and 1500 volt DC, below 69,000 volt (DC and AC))
MPPT	maximum power point tracker
MQF	(PV) module quality factor
NREL	National Renewable Energy Laboratory
NSS	normal sea state
O&G	oil and gas
O&M	operation and maintenance
OPEX	operational expenditures
PCS	power conversion system
PCPT	piezocone penetration test
pH	level of acidity
PID	potential induced degradation
POA	plane of array
POC	point of connection
PPE	personal protection equipment
PV	photovoltaic
RAMS	risk assessment method statement
RAO	response amplitude operator
ROV	remotely operated vehicle
RP	recommended practice
SAT	site acceptance test
SBR	setback ratio
SCADA	supervisory control and data acquisition
SLS	serviceability limit states

Abbreviation	*Meaning*
STC	standard testing conditions (air mass AM 1.5, irradiance 1000 W/m², temperature 25 °C)
TMA	Texel-Marsen-Arsloe
TMY	typical meteorological year
UHMWPE	ultra high molecular weight polyethylene (also HMPE)
ULS	ultimate limit states
Vmp	voltage at maximum power
Voc	open circuit voltage
VST	vicat softening temperature

SECTION 2 ENVIRONMENTAL AND SITE CONDITIONS

2.1 General

This section provides requirements, recommendations and guidance on how to assess environmental and site conditions, to be used for design of FPV systems.

Environmental and site conditions consist of all the natural phenomena and local aspects which may influence the design of an FPV system. This encompasses virtually all of the natural phenomena on a particular site, including, but not limited to, meteorological conditions, limnological and oceanographic conditions, water depths, soil conditions, seismicity, biology, ground conditions, water quality, contamination, water basin topography, bathymetry, waterproofing and various human activities.

Guidance note:

The meteorological, limnological and oceanographic conditions which may influence the design of a floating solar structure consist of phenomena such as wind, waves, current and water level. These phenomena may be mutually dependent, and for the three first of them, the respective directions are part of the conditions that may govern the design. Micro-siting of the solar structure within a solar plant requires that any local wake effects from adjacent solar sections are part of the site conditions at each individual location in the system.

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2.2 Wind

To allow safe design of FPV systems, the operationally relevant and extreme wind conditions shall be specified. Guidance for assessing the wind climate can be found in DNVGL-RP-C205 Sec.2. National standards, such as Eurocode EN 1991, ASCE-7 and AS 1170.2, may also be used as reference. The selection of a wind climate from standards, codes, and recommended practices shall be substantiated for each site in order to justify any interpretations of these documents.

As building codes and standards do not exactly describe the conditions and specificities of FPV systems, there will be a mismatch between the wind models and the actual conditions. It is therefore recommended to acquire data from project sites to apply in the FPV project design phase and allow improving the current available wind models. If these data are acquired before FPV project construction they will benefit the project and if data are acquired during the operational phase, they may benefit the improvement of wind models for future projects.

Wind conditions shall be used as an input for the design, see [4.4.2] for wind loads.

2.2.1 Wind modelling

The factors and data included in the following subsections have an impact on the design of the FPV project and shall be taken into account when assessing wind conditions for an FPV project location: reference wind speed, wind profile, turbulence, coherence and transient effects.

2.2.1.1 Reference wind speed

The wind speed varies along time and vertical elevation:

- Averaging period: the 10-minute mean wind speed U_{10} and the standard deviation σ_U of the wind speed, both referring to a specified reference height. In the short term, i.e. over a 10-minute period, stationary wind conditions with constant U_{10} and constant σ_U are assumed to prevail.
- Height: a reference height of 10 m is commonly used for the wind climate.

The specified reference height for the wind speed can be the FPV system height or any other height in which wind data happen to be recorded. Converting data to the same height and averaging period is important when assessing data from different sources. Wind data may be obtained via DNVGL-RP-C205 or national codes which (in Europe) typically use 10 min or 1 hr wind at 10 m height.

Mean wind speeds based on averaging periods different than 10 minutes may be used for representation of the wind climate instead of the 10-minute mean wind speed U_{10}, for example the 1-hour mean wind speed.

For hydro dams and reservoirs, comprehensive studies on wind and expected wave characteristics are often publicly available. This information may be retrieved from relevant parties, when available, and used in the design.

2.2.1.2 Wind profile

The variation of wind speed with vertical elevation is described by the wind profile. Typically, wind speeds are given at 10 m height, which should be converted to the height of the structure. For an FPV system this would typically be between 0.5 m and 5 m height. When using a standard wind profile from applicable standards, there can be considerable uncertainties for low heights due to the effects of surface roughness and waves. Wind profiles may be retrieved from DNVGL-RP-C205 or relevant national codes. The methodology and the applied assumptions used to define the wind profile for an FPV project location shall be documented. A comparison of the outcomes of different models may be done as it provides a bandwidth against which the chosen outcome can be assessed.

2.2.1.3 Turbulence

The wind speed under stationary 10-minute conditions in the short term follows a probability distribution whose mean value is U_{10} and whose standard deviation is σ_U.

The turbulence intensity is defined as the ratio σ_U/U_{10}.

The 10-minute mean wind speed U_{10} is a measure of the intensity of the wind.

The standard deviation σ_U is a measure of the variability of the wind speed about the mean. When special conditions are present, such as tornados and tropical cyclones, a representation of the wind climate in terms of U_{10} and σ_U may be insufficient.

The short term 10-minute stationary wind climate may be represented by a wind spectrum, i.e. the power spectral density function of the wind speed process, S(f). S(f) is a function of U_{10} and σ_U and expresses how the energy of the wind speed is distributed between various frequencies.

The type of wind spectrum, or the power spectral density, should be considered. The power spectral density is useful for this purpose. Guidance on power spectral density models may be found in DNVGL-RP-C205 [2.3.4] and DNVGL-RP-C205 [2.3.5], which also contains recommendations for the integral length scale that constitutes an important property of any power spectral density model.

It should be ensured that representation of the wind in the low frequency range is adequate, meaning the range of natural frequencies of the mooring system. This includes, but is not limited to, an adequate representation of power spectral density in the low frequency range as well as adequate models for representation of gust events.

Guidance note:

Various power spectral density models exist, usually expressing the power spectral density in terms of parameters such as the mean wind speed with some averaging period, for example the 10-minute mean wind speed U_{10}, and the standard deviation σ_U of the wind speed. Because U_{10} and σ_U vary with height above water level, the power spectral density is also a function of this height.

For floating structures, low frequency motion components and response components are expected.

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2.2.1.4 Coherence

The correlation between wind speeds at separated points in space may be of importance for large FPV systems and should be considered during the estimation of wind loads as described in [4.4.2]. Coherence spectra may be used for this purpose. Different integral length scales may apply for longitudinal, lateral and vertical separations. Models for coherence spectra are provided in IEC 61400-1 Sec.6 and appendix C.

2.2.1.5 Transient effects

When the wind speed changes or the direction of the wind changes, transient wind conditions can occur. Transient wind conditions are wind events which by nature fall outside of what may be represented by stationary wind conditions.

Examples of transient wind conditions are:

- gusts
- squalls
- extremes of wind speed gradients
- strong wind shears
- extreme changes in wind direction
- simultaneous changes in wind speed and wind direction such as when wind fronts pass.

2.2.2 Wind data

Wind data may be obtained either from measurements, hindcast or based on tabulated probability distributions from DNVGL-RP-C205 or relevant national codes. The nearby sheltering shall be considered when applying hindcast and tabulated probability distributions. The effect of sheltering may cause deviation when comparing these type of data sources to measurement.

The following parameters for the wind should be determined:

- probability distribution of wind speed at certain height and relevant averaging period
- distribution of wind direction
- vertical wind speed profile
- turbulence intensity I
- wind spectra
- wind shear
- extreme gust (e.g. 3-seconds wind) at the design wind speeds.

2.3 Waves

2.3.1 General

The aim of this subsection is to provide considerations and recommendations for assessing relevant wave conditions influencing the design of FPV systems, which are assumed to be located on inland water bodies or near shore locations. Only brief descriptions are provided in this subsection, while more in-depth descriptions may be found in the following references:

- DNVGL-RP-C205 Sec.3
- ISO 19901-1 (2015), appendix A.5
- Shore Protection Manual volume 1-1 (1984), chapter 3
- Coastal Engineering Manual – Part II (2015)
- IEC TS 62600-2, Section 6.

The main reference for wave conditions is DNVGL-RP-C205, which provides general description of waves, modelling and application mainly for offshore conditions.

Wave conditions which should be considered for structural and mooring design purposes, may be described either by deterministic design wave methods or by stochastic methods applying wave spectra.

- Deterministic: regular waves defined by wave height and wave period (H and T).
- Stochastic: irregular waves obtained from a wave spectrum with the energy distributed on a large number of wave frequency components. The key parameters are significant wave height (H_s) and peak wave period (T_p).

The type of wave modelling depends on application and whether the structure response is dynamic or static:

- Regular wave modelling may be used for quasi-static response of structures where dynamic effects can be neglected.
- Irregular wave modelling shall be used for structures with significant dynamic response.

Both regular and irregular waves can apply either linear or non-linear wave models.

Guidance note:

A wave model describes the surface wave elevation and the fluid particle kinematics. The simplest wave model is obtained by assuming the wave height to be much smaller than both the wave length and the water depth. This model is referred to as linear wave theory, sinusoidal wave theory or Airy wave theory.

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Wave barriers may be a design solution to reduce the wave conditions on a floating structure. Such barriers shall be properly designed for the extreme conditions using appropriate design codes. Note that the transformed wave conditions behind the barrier, acting on the structure, shall be assessed.

2.3.2 Regular waves

2.3.2.1 General

Regular waves may be used to describe one single individual wave crest or wave trough, or a wave train of similar shaped waves. A regular travelling wave is propagating with permanent shape. It has a distinct wave length, wave period, and wave height.

Regular wave models may be used to describe for instance:

- extreme waves caused by tsunami or landslides
- regular waves due to passing vessels.

In addition, a regular wave may be used to represent the deterministic largest individual wave identified from an irregular wave time series, which is applicable for quasi-static structural response.

The use of advanced non-linear wave models shall be considered for very shallow water and steep waves. Guidance on when to apply advanced models and description of the models may be found in DNVGL-RP-C205 [3.2], edition 2019.

Guidance note:

Advanced wave models describe non-linear regular waves, which are asymmetric, meaning that the wave crest is larger than the trough. Examples of non-linear wave models are for instance higher order Stokes waves and stream function wave theory, cnoidal waves and solitary waves.

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2.3.2.2 Passing vessels

Regular waves due to passing vessels should be considered. The size, type and speed of vessel should be used to determine the wave height. The water depth and type of water body should be considered to set limitations on what type of vessel one needs to consider. If a harbour is nearby with large passing vessels, the occurrence of large waves shall be considered.

2.3.2.3 Extreme waves

The potential for earthquake-induced waves, also known as tsunamis, shall be assessed. Likewise, the potential for tsunami-like waves which are not necessarily initiated by earthquakes, should also be assessed. This could be caused by e.g:

- underwater landslides
- flood events in river valleys caused by dam or dike failure.

Guidance note:

Tsunamis have very long periods and behave like shallow water waves even when passing through deep parts of the ocean. Tsunami risk can be particularly relevant for FPV project sites in near-shore locations, while landslide-induced waves can be relevant for hydro dam reservoirs.

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2.3.2.4 Maximum wave height and breaking waves

Breaking waves shall be assessed when wave breaking is expected to occur in such a manner that it governs the FPV system design. The impact on design and modelling may be found in DNVGL-RP-C205 [3.4.6], edition 2019.

There is a limit for the maximum wave height at a certain wave length due to the finite water depth, which may be used to determine the potential for breaking waves. The highest regular wave height H_b on a plane waterbed is given by:

$$\frac{H_b}{\lambda} = 0.142 * \tanh\frac{2\pi h}{\lambda} \qquad (2.1)$$

where λ is the wave length corresponding to water depth h.

Furthermore, the maximum wave height, limited by breaking, depends on the water depth, h:

$$H = 0.78h \qquad (2.2)$$

These simple relations may be used to determine the limitation of wave formation in finite water depth, and may also be used as a rule of thumb in relation to the formation of irregular sea states.

2.3.3 Irregular waves

2.3.3.1 Local wind generated waves and swell

Wind generated waves are irregular and random in shape, height, length, and speed of propagation. This shall therefore be described by an irregular wave model.

The wave conditions in a sea state may be characterized by two components, wind sea and swell:

- Wind sea: waves generated by the local wind.
- Swell: long waves which have propagated over a long distance, generated by storms at great distance from the site.

Wind sea, or local wind generated waves, is the type of waves which shall be considered for inland water bodies. Wind sea is also likely to dominate in a protected coastal area, however, swell may be considered as it could be transformed from the surrounding ocean depending on the location.

Guidance note:

In the ocean, it is common to assume that the water surface is stationary for a duration of 20 minutes to 6 hours. A stationary sea state may be characterised by a set of environmental parameters such as direction, the significant wave height, H_s, and the peak period, T_p.

A linear irregular wave model is a sum of many linear wave components with different amplitude, phase, frequency and direction. The phases as well as amplitudes are random with respect to each other. The amplitudes of the linear wave components are distributed by frequency, which is described by a wave spectrum, $S(\omega)$. The wave spectrum distributes the wave energy by frequency. Several types of standard wave spectra exist to describe irregular waves, and they all have different application.

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2.3.3.2 Presence of irregular waves

For inland water bodies with short fetch lengths and limited waves a detailed wave assessment may not be needed. If waves are not relevant for the site, this shall be stated in the design basis for the project.

This may be assumed based on fetch length, low wind speeds or water depth and shall be justified and documented.

Longer fetch distances combined with sustained wind of long duration creates wind-generated irregular waves, which is relevant for both inland water bodies and coastal areas.

Coastal areas may potentially be influenced by swell, transformed from the surrounding ocean depending on the location.

River locations, in proximity of estuaries, may be influenced by spring tides.

2.3.3.3 Wave spectra

The JONSWAP spectrum should be used to describe wind-generated waves of limited fetch. The JONSWAP spectrum applies a peak enhancement factor, γ, which describes the width of spreading about T_p. If no particular values are given for γ, the value should be determined from H_s and T_p for wind dominated sea according to DNVGL-RP-C205 [3.5.5.5].

The energy of swell is more focused around T_p compared to wind generated sea. The JONSWAP spectrum should be used for swell, then by selecting a high value for the peak enhancement factor, e.g. $\gamma = 10$.

The finite water depth Texel-Marsen-Arsloe (TMA) spectrum, for non-breaking waves, should be used as an adjustment of the JONSWAP spectrum, improving the modelling of waves in more shallow water, see DNVGL-RP-C205 [3.5.6].

Other validated methodologies may be used to describe wave spectrum, if properly justified and documented.

2.3.3.4 Spreading

The wave energy can also be distributed by direction (about the main direction of propagation). This phenomenon is referred to as wave spreading. Standard spreading functions are found in DNVGL-RP-C205 [3.4.4]. Simplified modelling may be used for wave spreading, if properly justified and documented.

2.3.3.5 Short-term description waves

The short-term description of individual wave height, H, shall be considered for irregular waves.

Guidance note:

The wave height H of a wave cycle is the difference between the highest crest and the deepest trough between two successive zero-up-crossings of the sea surface elevation. The arbitrary wave height, H, under stationary conditions in the short term follows a probability distribution which is a function of the significant wave height, H_S.

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In deep waters (depth >2 times the wave length) for narrow-banded wave processes, the short-term probability distribution of the arbitrary wave height, H, should be taken from the Rayleigh distribution:

$$F_{H|Hs}(h) = 1 - \exp\left(-\frac{2h^2}{H_s^2}\right) \quad (2.3)$$

The most probable maximum wave height, H_{MPM}, may be calculated by the following relation:

$$H_{MPM} = H_S\sqrt{\frac{1}{2}\ln N} \quad (2.4)$$

Here N is the number of waves in the time series record, which may be estimated as the ratio between the duration of the sea state, D, and the mean zero-up-crossing period, T_z, of the waves:

$$N = D/T_z \quad (2.5)$$

The value T_z may be derived from the wave spectra with further guidance given in DNVGL-RP-C205 [3.5.5.4]. With $N = 1000$, a ratio between H_{MPM} to H_S of 1.86 is obtained.

Guidance note:

In shallow water, the wave heights are limited by the water depth. The Rayleigh distribution of the wave heights become distorted in the upper tail to approach this limit asymptotically. The use of the unmodified Rayleigh distribution for representation of the distribution of wave heights in shallow water may therefore be on the conservative side.

In shallow water with constant seabed slope, the Battjes and Groenendijk distribution may be used to assess the probability distribution of the arbitrary wave height, H, conditional on the significant wave height, H_S. However, the distribution should be validated by measured site-specific wave data. The Battjes and Groenendijk distribution is based on the Weibull distribution and is described more in detail with full equations in DNVGL-ST-0437.

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2.3.4 Wave conditions for design

2.3.4.1 General

A long-term description of the significant wave height H_S is necessary for establishing design wave loads corresponding to a certain return period. A probability distribution for the annual maximum H_S should be established. A Weibull distribution or Gumbel extreme value distribution may be used.

Statistics for the wave direction may also be relevant and shall be assessed.

For structures that are sensitive to dynamic excitation, also the peak period T_P shall be assessed. A probability distribution of T_P given H_S is typically used. A 2-dimensional scatter diagram for probability of occurrence with bins of H_S and T_P is typically used to represent the long term wave conditions.

In deep waters, the range of T_P that should be associated with H_s is found in DNVGL-ST-0437:

$$11.1\sqrt{\frac{H_S}{g}} \leq T_P \leq 14.3\sqrt{\frac{H_S}{g}} \tag{2.6}$$

2.3.4.2 Extreme sea state

The extreme sea state (ESS) is characterised by a significant wave height, a peak period and a wave direction. The significant wave height, Hs_{ESS}, should be established as the unconditional significant wave height with a specified return period, determined from the distribution of the annual maximum, H_S.

The range of peak periods, T_P, appropriate to each of these significant wave heights should be considered. Design calculations shall be based on values of the peak period which result in the highest loads or load effects in the structure. If site specific statistics are not available, the range from eq. (2.6) should be assessed.

2.3.4.3 Normal sea states

The normal sea state (NSS) should be used for calculation of fatigue loads. The normal sea state is characterised by a significant wave height, a peak period and a wave direction. A series of normal sea states should be considered that represent the distribution of H_S within 1 year. It should be ensured that the number and resolution of these normal sea states are sufficient to predict the associated fatigue damage.

The range of peak periods, T_P, appropriate to each significant wave height should be considered. H_S should be considered by:

- scatter diagram, or
- sensitivity to peak period using equation (2.6) and taking the worst result for each H_S.

2.3.4.4 Extreme wave heights

The extreme wave height conditional on the H_S should be considered. The associated wave period for extreme individual wave height is described in DNVGL-RP-C205 [3.7.4].

Also, the extreme regular waves, e.g. from tsunamis and passing vessels, should be considered.

2.3.5 Wave data for design

2.3.5.1 General

This subsection provides an overview of the methods that may be used to obtain the wave data for design when the formation of irregular waves is of concern to the structure design.

2.3.5.2 Measurements

The most reliable wave data is obtained by measurements. Some examples of measurement equipment are pressure sensors, wave buoys, and acoustic wave profilers bottom mounted. In the absence of reliable wave data, alternative methods may be advanced hindcast modelling or estimation formulas. Both these alternative methods rely on several assumptions and simplifications.

Guidance note:

Wave measurements are valuable even if the measurement periods are too short to establish long term distributions, which would require several years of measurements. Such measurements may be used to calibrate and validate the estimation methods. Also, note that wave measurements for the FPV application may be more simple than for offshore application, being near shore and often at shallow water. More guidance about wave measurement may be found in ISO 19901-1:2015 section A5.4.

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2.3.5.3 Hindcast

Hindcast modelling is widely used for offshore applications and is usually calibrated against measurements. Hindcast means to model the waves resulting from the wind generated by the atmospheric pressure data measured in the past. More information about hindcast modelling is provided in ISO 19901-1:2015 section A5.

2.3.5.4 Estimation of wave conditions

Wave data may also be estimated based on wind speed and fetch length. These methods rely on several assumptions and simplifications, e.g. constant wind speed, and for duration long enough to obtain equilibrium of the sea state. Wave conditions may be estimated using the empirical formulas of Breugem and Holthuijsen (2007), as provided in the guidance note below. There are also empirical formulas for fetch-limited waves described in the Shore Protection Manual volume 1-1 (1984), chapter 3, section V, which also may be used. The estimation can be improved by using numerical modelling. If estimation from wind speed is used, it shall be properly documented and justified.

Guidance note:

The growth of fetch limited waves in water of finite depth is studied by Young and Verhagen (1996). The study is based on measurements of Lake George, which is 10 km wide and 20 km long, with a relatively uniform bathymetry of approximately 2 m depth on average. An empirical model was fit to the data points, a model that converges to the JONSWAP spectrum in deep water. The model provides relatively good results when compared with measured data, however there are discrepancies and sources of error which are discussed in the paper.

The model was later revisied by Breugem and Holthuijsen (2007), which is given with formulas below. The model provides normalized significant wave height and peak period:

$$H_{S0} = \frac{H_S \times g}{U^2} = 0.240 * \left(\tanh\left(A1\right) \tanh\left(\frac{B1}{\tanh A1}\right)\right)^{0.572} \tag{2.7}$$

$$T_{P0} = \frac{T_P \times g}{U} = 7.69 * \left(\tanh\left(A2\right) \tanh\left(\frac{B2}{\tanh A2}\right)\right)^{0.187} \tag{2.8}$$

With the following coefficients:

$$A1 = 0.343 * h_0^{1.14}$$

$$B1 = 4.41 * 10^{-4} * F_0^{0.79}$$

$$A2 = 0.1 * h_0^{2.01}$$

$$B2 = 2.77 * 10^{-7} * F_0^{1.45}$$

which are expressed in terms of of normalized fetch and water depth:

$$F_0 = gF/U^2 \tag{2.9}$$

$$h_0 = gh/U^2 \tag{2.10}$$

In which the fetch, F, is given in m and the wind speed, U, given in m/s at 10 m height. Finally, the values of H_s and T_p are obtained:

$$H_S = \frac{H_{S0} \times U^2}{g} \tag{2.11}$$

$$T_P = \frac{T_{P0} \times U}{g} \tag{2.12}$$

Numerical methods may also be applied, as elaborated by Booij, Holthuijsen and Ris (1996), where the waves observed in the study are estimated with promising results.

When H_S is established from wind speed, the H_S for a defined return period may be established based on the wind speed at the same return period. This wind speed may be taken directly from the inverse annual distribution of wind speed.

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2.3.5.5 Wave transformations

Numerical wave transformation may be used to transform waves from a location with known data to another location. This is highly relevant for coastal areas. The modelling requires bathymetry data and can account for effects like refraction, diffraction, reflection, shoaling and breaking waves. Guidance may be found in DNVGL-RP-C205 [3.4].

2.4 Current

For the following parameters on water current, available data shall be collected and, if necessary, measurements should be performed for additional data. This data shall be taken into account for the FPV system design:

- water current directions
- water velocity profile (speed versus depth)
- typical water velocity
- maximum water velocity and probability of exceedance (especially in case of flood and hydro dam operations).

For each specific FPV project site and parameter, the appropriate measuring methodology shall be selected.

The Velocity-area and Acoustic Doppler Current Profiler methods are recommended methods to determine water current profiles.

The following standard and guideline documents may be used as a reference to assess water current:

- ISO 1070/BS 3680 – Methods of Measurement of Liquid Flow in Open Channels.
- World Meteorological Organization – 'Guide to Hydrological Practices', Chapter 5: Surface Water Quantity and Sediment Measurement.
- DNVGL-RP-C205 Sec.4 for oceanic water currents.

The locations of the water current measurements should be chosen such that they can be used for both the currents affecting the floating structure as well as the currents affecting anchoring positions.

Gathered data and measurement data may be used in 2D or 3D simulation models to develop a representation of the water flow of the site.

2.5 Snow and ice accretion

Snowfall and other forms of precipitation on the FPV array shall be assessed. For FPV systems, the impact of ice around and under the FPV system shall be investigated for the following two aspects:

- interaction of ice with the FPV system and its components
- horizontal loads on the structure.

For the following recommendations DNVGL-ST-0437 can be consulted for further guidance. The ice thickness forms an important parameter for calculation of ice loads. Ice thickness should be determined based on local ice data, as available in an Ice Atlas or as derived from local frost index data.

Besides the ice thickness, the following characteristic data should be determined:

- ice bulk salinity
- ice brine volume
- ice porosity
- ice temperature
- ice density
- ice strength
- ice flow velocity.

For modelling of ice thickness related to inland water bodies, see DNVGL-ST-0437 [2.4.10].

The long-term mean value of the annual maximum ice thickness may be interpreted as a measure of the ice thickness associated with a 'normal winter'.

Water icing may become a problem when the water temperatures fall below -2°C. Floating ice masses that are formed elsewhere can survive though when the water is considerably warmer. When considering icing on a structure, wind strength and air temperature are of prime importance; however, icing is unlikely to occur until water surface temperatures fall below 4°C.

In FPV project sites where snowfalls and icing are likely to be severe or where loading from floating ice is expected to occur, reference shall be made to local codes and standards.

DNVGL-ST-0437 should be consulted for the assessment of ice flow velocities and sea ice loads. For recommendations for horizontal ice loads on structures, see IEC 61400-3-1 Annex D.

Further standards that provide guidance on ice phenomena are ISO 19901-1 and ISO 19906.

2.6 Fouling

2.6.1 General

The forms of fouling that the FPV system could encounter shall be investigated. The impact of fouling on the soiling level of the PV modules, the system's material quality and drag coefficients should be assessed.

Guidance note:

Fouling can come from the air, from the water and, in case of continuous water flows, from upstream. Some examples are dust soiling, bird droppings, animal presence, marine growth, floating organic materials (plants, trees, etc.) and waste.

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2.6.2 Marine growth

The potential for marine growth on structures and power cables shall be addressed and linked to potential influence on the hydrodynamic loads, the dynamic response, the accessibility and the corrosion rate of the components. Where sufficient information is available, the loading coefficients should be selected based on the nature of the marine growth. DNVGL-RP-C205 [6.7.4] and DNVGL-ST-0437 [2.4.11] may be used for guidance. Where necessary, site-specific studies should be conducted to establish the expected marine growth type, thickness and depth dependence. The marine growth assessment should be used to choose appropriate methods of controlling and mitigating marine growth.

Guidance note:

Applying to both fresh and salty waters, the plant, animal and bacteria life at the site causes marine growth on structural components in the water. Marine growth adds weight to a structural component and influences the geometry and the surface texture of the component.

Marine growth may broadly be divided into hard growth and soft growth. Hard growth generally consists of animal growth such as mussels, barnacles and tubeworms, whereas soft growth consists of organisms such as hydroids, anemones and corals. Marine growth may also appear in terms of algae and aquatic plants. Marine organisms generally colonise a structure soon after installation, but the growth tapers off after a few years.

The thickness of marine growth depend on the position of the structural component relative to the water level, the orientation of the component relative to the water level and relative to the dominant current, the age of the component, and the maintenance strategy for the component. Experience in one area of the world cannot necessarily be applied to another. Marine growth also depends on other site conditions such as salinity, oxygen content, pH value, current and temperature.

Methods of controlling marine growth include the use of anti-fouling paints, scraping with the hand or mechanical removal by water- or air-jetting.

The corrosive environment is normally modified by marine growth in the upper submerged zone and in the lower part of the splash zone of the structural component. Depending on the type of marine growth and on other local conditions, the net effect may be either an enhancement or a retardation of the corrosion rate. Marine growth may also interfere with systems for corrosion protection, such as coating and cathodic protection. For guidance on corrosion protection, see DNVGL-RP-0416.

The rate of encrustation on a structure and the species of organism present depend on the temperature of the environment, higher temperatures promoting more vigorous growth.

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2.7 Ecology

In order to determine the potential impact of an FPV system on the site's ecology, an environmental impact assessment shall be carried out by competent environmental experts and professionals. All mechanisms affecting the site's environment shall be assessed and whether they cause primary or secondary, direct or indirect, short-term or long-term effects. The FPV system shall then be planned and designed to incorporate measures to minimize any undesirable impact on the site's ecology.

See [7.3.3] for more considerations on environmental impact assessment.

Guidance note:

The construction, operation, maintenance, and decommissioning of FPV systems can cause a substantial impact on both the marine and terrestrial environment. Although the primary interface with the environment leads to a change of the water regime in the vicinity of the FPV, there are many other mechanisms, like failures or accidents, which can result in changes of environmental conditions.

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2.8 Other environmental conditions

Relevant information and data shall be obtained on any other environmental factors that can affect the operation of an FPV system and it shall be considered in the design of the system. Tthis data shall include, where appropriate, records and predictions of:

- Irradiance. Data should be used to estimate the thermal balance between incoming, reflected and emitted radiation and as a result the cooling capacity of an area of water and the potential evaporation, see [3.2.3] for meteorological measurement stations and [3.2.3.2] for pyranometer specifications.
- Temperature. To assess a potential cooling effect of the water on the PV modules, temperature profiles (including extreme values and their return periods) of the ambient air, PV module surface and the water surface should be determined, refer to [3.2.3] for meteorological measurement stations, [3.2.3.6] for ambient temperature sensor specifications, [3.2.3.7] for PV module temperature sensor specifications.
- Humidity and salinity. The variations in relative humidity and salinity expected during the life of the structure should be assessed, to properly determine risk of corrosion of materials, refer to [3.2.3] for meteorological measurement stations and [3.2.3.8] for humidity sensor specification.
- Water composition. Chemical and bacteriological analyses of the water should be made at an early stage of the site investigations, with particular attention being paid to potentially corrosive elements aggressive to floating structures such as chloride and sulphate ions.
- Water turbidity. Turbidity should be considered with special reference to sediment movement. The most rapid changes in turbidity usually occur during dredging operations and the consequences should be borne in mind during the planning of the initial site preparation and maintenance dredging. The possibility of degradation of the floating structure caused by redeposited harmful substances should be considered. Detailed consideration should also be given to the area of soil disposal, because of the possibility of dispersion and redeposition back into the dredged area.
- Water pollution.
- Visibility. Poor visibility can have severe consequences in relation to navigation in inland waters and estimates of the expected duration should be made. Caution should be used when studying visibility reports from a station not directly on the coast as the phenomenon known as sea fog is usually not experienced more than 3 km to 4 km inland and erroneous data can therefore be extracted for navigation and piloting purposes.
- Neighbouring activities. Any form of activities that can have an impact on the FPV system, or on which the FPV system can have an impact, shall be determined and the implications on the FPV system shall be assessed.

Guidance note:

Additional considerations on the factors mentioned above:

- Irradiance. The thermal balance equations can be used to estimate the cooling capacity of an area of water and the potential evaporation. Also, the life expectancy of bacteria released to the water is thought to be highly dependent on the intensity of solar radiation, particularly in the ultraviolet wave lengths. The calculation or measurement of this mortality is important in water outfall design for effluents such as domestic sewage. On the other hand, algae growth thrives by solar radiation and may thus be expected to reduce with less solar radiation.
- Temperature. In coastal regions there is usually a well-defined seasonal water temperature variation. Throughout the year the water column tends to be isothermal due to strong turbulent mixing. In areas where there is a thermal effluent or in estuaries with high freshwater discharge significant stratification can exist. Temperature variation has effects as follows:
  - Corrosion. Higher temperatures increase the rate of iron oxide formation and can have a significant effect on bacterial corrosion.
  - Effluent dispersion. The density of seawater is a function of its temperature and salinity and is a fundamental parameter to be considered when modelling the behaviour of an effluent immediately after release.
- Water turbidity. Turbidity is usually caused by suspended clay or silt particles, dispersed organics, and micro-organisms. A lower water temperature increases the amount of sediment that can be transported in suspension due to the viscosity change. Dredging operations can cause the release of harmful substances that are locked into fine sediment particles and can remain attached when dredging operations put the material into suspension.
- Water pollution. Some trade effluents, if insufficiently diluted, can accelerate deterioration of the floating structure. Pollution can act as nutrients or deterrents to bacteria, significantly affecting microbial induced corrosion.
- Visibility. The reduction of atmospheric transparency and therefore visibility is caused by two predominant factors:
  - a suspension of extremely small dry particles, called haze
  - suspended microscopic water droplets or wet hygroscopic particles, known as mist.

  Fog is a term conventionally applied when the horizontal visibility at the earth’s surface is reduced to less than 1 km. Visibility often changes sharply near the coast between the widely different regions of sea and land.

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2.9 Water depth

2.9.1 General

The water depth at the site, including variations in the water depth, should be determined as prescribed by ISO 19901-1-2015.

The range of water depths at a particular site shall be taken into account in the design of structures as it affects several parameters, including:

- environmental actions on the structure
- elevations of boat landings and fenders
- mooring forces for taut or vertically moored floating structures.

For the purpose of design or assessment, the water depth may be considered to consist of a stationary component, this being the water depth to a reference level (e.g. in hydro dams or lakes) or chart datum (e.g. for near shore sites the lowest astronomical tide-LAT or mean sea level-MSL), and variations with time relative to this level. Water level variations in shallow water should be more carefully considered, as they can have a considerably larger impact from droughts and floods, including risk of stranding and wave breaking forces, as opposed to a relatively minor impact in deep water.

Guidance note:

In lakes with seasonal variations or hydro dam locations the variations occur due to inflow and outflow of water. The near shore variations are due to the astronomical tide and to the wind and atmospheric pressure, which can create storm surges (being either positive or negative). Other variations in water level can result from long-term climatic variations, sea floor subsidence or episodic events such as tsunamis.

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2.9.2 Bathymetry

Bathymetric surveys are conducted taking a series of measurements of water depth and water bank slopes at known locations over the area of interest. Assessment of variations in bathymetry shall be performed in order to understand the range of possible water depths applicable in the vicinity of the floating structure and the potential for depth-limited wave breaking to be a controlling effect on design wave conditions.

For application in an FPV system design process the bathymetric survey should be as recent as possible, particularly in areas of construction or areas with mobile sediments. As a general rule, site surveys should be considered out-of-date after six months. In areas without waterbed mobility and where there has been no known activity a longer validity period may be considered.

Automatic systems, which measure location and water depth, shall be regularly calibrated as part of a quality control system. It is recommended to measure water depth and water bank slopes using echo sounders which record a continuous profile of the waterbed being equipped on a survey vessel. Only purpose-built hydrographic echo sounders should be used. The use of a multi-beam echo sounder is preferred, whereas the choice for a single or multi-beam echo sounder should be made and justified according to the expected depth and expected variations of the waterbed. Multi-beam technology should be used for improved results in deep or uneven waterbeds. The use of single beam echo sounder or LiDAR airborne acquisition should be justified by a dedicated assessment. Under suitable water conditions, like low water turbidity, shallow or flat waterbeds may be surveyed with single beam echo sounder or LiDAR airborne acquisition techniques. When not used correctly, echo sounders may give misleading results in areas of very soft mud, which sometimes occur in estuaries. In these cases other methods, such as low frequency sounders, may be used or a multi-beam echo sounder should be selected adequately on frequency range and calibration. For additional recommendations on the assessment of ground conditions, see [2.12].

Direct measurements should be performed if the records of the echo sounder are subject to too high uncertainties and if direct measurements will provide lower uncertainties. This can occur when sounding over a particularly soft seabed or when large quantities of water plants are present. Such measurements are usually made by hand-lead line, graduated pole or sweeping with a horizontal wire.

A bathymetric survey for an FPV project site shall be made at an appropriate profile spacing, using appropriate technology, depending on the project phase and the type of water body. For inland water bodies, profile spacing using a single-beam echo sounder should be chosen between 5 m and 1 m in and around the proposed position of the structure and at the proposed anchoring locations. For multi-beam echo sounder technology, the line spacing should be adjusted as a function of water depth and coverage across the site.

The direction in which profiles are run should be dependent on the purpose of the survey. For the usual purpose of delineating depth contours as accurately as possible, surveying across the anticipated contours as near as possible at right angles is recommended. As recommended survey practice, additional profiles should be run at right angles to the chosen direction at a wider spacing, for example 5 to 10 times, to check lines and reveal the presence of features such as sand waves, which, because of the original choice of direction, might not have been identified.

See the following standards: BS 6349-1-2000, DNVGL-ST-N001, DNVGL-ST-N002, ISO 19901-10, ISO 21650:2007 and ISO 19901-6.

Guidance note:

Bathymetry imposes constraints on currents and waves and therefore on erosion and accretion. Erosion and accretion of the waterbed can impose significant changes in bathymetric features, both seasonally and over the lifetime of any project. The rate of change in the bathymetry depends on the balance between erosion and accretion, which themselves depend upon the waves, currents and sediment budget. The complicated interaction between waves, currents and bathymetry introduces considerable uncertainty into the predictions of any changes. Recommendations related to waterbed movement and scour are addressed in [2.10].

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2.9.3 Water level

Water levels at the location of the FPV shall, where applicable, be determined for:

- highest impounded level for an enclosed basin (HIL)
- lowest impounded level for an enclosed basin (LIL)
- highest recorded tide (HRT)
- mean high water springs (MHWS)
- mean low water springs (MLWS)
- highest astronomical tide (HAT)
- lowest astronomical tide (LAT)
- lowest recorded tide (LRT).

The design water level variation should be based on the HIL and LIL for an enclosed basin or the MHWS and MLWS for near-shore applications, unless otherwise required for the operation of the FPV system. It is possible that the LIL is the zero-water level.

In river locations, in estuaries or in water bodies connected to these, spring tides should be taken into account.

In other cases, the operating water level should be agreed with the operator or owner of the enclosed basin.

A near-shore FPV system should be designed for an extreme condition based on the HAT and LAT plus an allowance to cover for atmospheric pressure and storm surge due to wind. Alternatively, if reliable values of HRT and LRT are available, these may be used instead.

Any predicted long-term or short-term rise or fall in general water level and water level variation speed should also be taken into account for both the design and the extreme conditions.

2.9.4 Storm surges

Storm surges are generated by wind- and pressure-induced effects in oceans and large lakes. A storm surge can both reduce and increase the water level beyond the astronomical tides. The extreme water levels shall be considered in combination with high waves.

Generation of surges is unrelated to tides and should be modelled as a separate stochastic process to be superimposed on tidal variations. A conservative estimate is obtained by adding extreme values for each component. In the feasibility phase an assessment should be done to determine the probability and impact of storm surges. For a more detailed assessment, recommended combinations of water level and metocean conditions are given in NORSOK N-003.

Guidance note:

Effects that can play a part in determining storm surge are wind set-up, reduced atmospheric pressure, rotation of the earth, coastline topography and storm motion. Of these, the largest effect is usually produced by wind set-up. Wind blowing over the sea induces a surface current that can lead to a pile-up of water along the coastline. Clearly, if the storm surge is forced to travel into a gradually narrowing area of sea between two land masses, the water level increases due to the funnelling effect of such a coastline.

For seas of limited extent, storm motion effects can be capable of exciting the resonances of the sea basin thereby increasing the storm surge level. For large bays, it is possible for the natural modes of oscillation of the bay to be excited as well and this can further enhance the surge level.

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2.10 Waterbed movement and scour

In any operation involving the alteration of the inshore hydrodynamic regime, the subsequent effects on sediment movement should be considered. This may include hydro-dam applications where sedimentation is expected over the lifetime of the asset, quarry lakes and dredging disposal lakes.

If possible, a comparison between historic information and recent data should be conducted and changes of depth and apparent movement of features should be studied to indicate the transportation of sediment.

Guidance note:

The natural parameters that define the rate and direction of sediment transport are prevailing currents, waves, bathymetry and the properties of the waterbed or water body sediment. Waves and currents are the agents responsible for entraining, transporting and depositing sediment. Bathymetry imposes constraints on currents and waves and therefore on erosion and deposition. A general appreciation of sediment transport in an area can be gained by studying old charts and photographs, including aerial views and by carrying out a preliminary inspection. Care should be taken to avoid being misled by seasonal or short-term effects.

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The methods and equipment used for the measurement and estimation of sediment load in rivers and reservoirs may be found in WMO-No.686. For local scour around a pile placed in non-cohesive sediment, DNVGL-ST-0126 App.D provides further guidance. For other structures or structures placed on cohesive sediment or in a wave dominated environment the prospect of scour developing should be predetermined by full scale or model scale experiences of comparable sites and geometries. In regions where water bank and waterbed materials are likely to erode, special studies of current conditions near the water bank and waterbed should be conducted.

In case of certain waterbed movement and accompanying risks, bathymetry studies should be repeated during the system’s operational life.

2.11 Waterproofing system

In case a waterproofing system is present or is planned to be installed in the water reservoir, relevant details about the location and size of the waterproofing system, and the boundary conditions for the design of the FPV system shall be obtained so that mitigation measures can be implemented to ensure the risks of damage to the waterproofing system are reduced to an acceptable level.

2.12 Ground conditions

For design of station-keeping systems and their components, such as anchors and mooring lines, a range of ground conditions should be defined. For each particular site-specific FPV project, the design of these station-keeping systems and their components shall be qualified for application in the actual site conditions.

The surface and subsurface soil conditions at and near the site of proposed works shall be assessed by conducting geological studies, geophysical surveys and geotechnical investigations. The studies should include an assessment of the characteristics of rock or soil formations, which can be retained by structures or provide their foundations.

The combination of geological, geophysical and geotechnical information should be used to develop a ground model which provides all necessary soil data for a detailed geotechnical design for the anchoring. The depth of the ground model below the waterbed and the collection of soil data needed for design should properly reflect the type and size of the foundation, in particular with respect to which parts of the soil are most important for the interaction between the anchors and the soil. Guidance on soil data needed for design of foundations of various commonly encountered types of structures may be found in DNVGL-RP-C212. Geohazards should also be captured in the ground model.

For soil investigations, the detailed requirements and recommendations given in DNVGL-ST-0126 [7.3], DNVGL-RP-C212 Sec.2, ISO 19901-8, ISO 19901-10 apply. Also, EN 1997-1 and EN 1997-2 or OSIG Guidance Notes (2014) may be consulted. The site investigation report should include borehole logs, results of laboratory tests and piezocone penetrometer test (PCPT) records (when acquired), together with interpreted geotechnical soil parameters. The choice of probing technique may depend on the project phase, data available and preferred anchoring technology. Profiling systems (e.g. sub-bottom profiler, sparker, etc.) and seismic profilers (e.g. ultra high resolution seismic) may be used in combination with PCPT. A geotechnically competent person or team should be responsible for determining the appropriate geotechnical soil parameters and the methodologies of investigation.

For the sake of accessibility, areas providing access to the construction site should be considered. Existing infrastructures like canals, old dikes, power cables, gas pipes, phone lines and water conduits should be identified to allow an assessment of their interference with the floating structure and station-keeping system. A suitable geophysical survey should be conducted to determine accurate locations and depths of existing infrastructures prior to investigation and installation in the area.

In case the ground investigation concludes that the ground may be contaminated with, for example, toxic materials or explosives from unexploded wartime ordinance, appropriate measures shall be taken to mitigate any risks associated with the contamination.

2.13 Earthquakes

The level of seismic activity of the area where the FPV system shall be installed can be assessed by local codes for seismic resistant design or on the basis of previous records of earthquake activity, as expressed in terms of frequency of occurrence and magnitude. Near-shore locations may be assessed using ISO 19901-2 as a reference. A first assessment may be done based on local codes for seismic resistant design and, for areas where detailed information on seismic activity is available, the seismicity of the area should be determined from such information. For areas where detailed information on seismic activity is not available, a probabilistic seismic hazard assessment shall be conducted by competent contractor to provide ground motion parameters. Such study requires a suitable evaluation of the soil geotechnical properties and may require complementary studies in case of inappropriate soil conditions or severe ground motions.

If the area is determined to be seismically active and the FPV system could be affected by the seismic activity an evaluation shall be made of the regional and local geology in order to determine the location and alignment of faults, epicentral and focal distances, the source mechanism for energy release and the source-to-site attenuation characteristics. Local soil conditions shall be taken into account to the extent that they may affect the ground motion. The seismic design, including the development of the seismic design criteria for the site, shall be in accordance with recognized industry practice.

SECTION 3 ENERGY YIELD ANALYSIS

3.1 General

This section presents a set of methodologies to appropriately estimate the energy yield for an FPV project. Other methodologies may only be used if properly justified, validated and documented.

An Energy Yield Analysis (EYA) is defined in this RP as the modelling of the average yearly expected energy production of an FPV system over the lifetime of the project.

The EYA is key to understanding the FPV system's expected energy production and performance throughout its operational lifetime, as well as the related risks and uncertainties.

An EYA shall be performed prior to the development of an FPV system. The EYA is carried out on an energy model comprising:

— *Meteorological resource data*

  It is recommended to perform an analytical review of different sources of meteorological data including on-site measurements, public databases, satellite-derived data and selection of high-quality option(s) for input into energy production simulations. Meteorological resources used as inputs to the energy model should be obtained, when possible and feasible for the project timeline, through on-site measurement. When use of on-site measurements is not feasible, satellite based meteorological resource data shall be used as a minimum. The process for meteorological resource data usage in the energy model is described in [3.2].

— *Energy production estimate*

  The energy production estimate shall include specific conditions and characteristics of the project as an input to the energy simulation, including but not limited to: layout, electrical design, PV modules, inverters, soiling losses and float technology.

  The energy production estimate shall include use of energy simulation software which follow industry recognised methodology for EYA. Some of the most commonly used simulation software in the solar industry are PVsyst, SolarFarmer, PVSol, Homer and System Advisory Model (SAM).

  The process for energy production estimates in the energy model is described in [3.3] to [3.8].

— *Uncertainty analysis*

  The uncertainty estimate shall include uncertainty for the resource data, energy simulation and losses calculation. Sensitivity analysis and downside risk analysis should be included to ensure that potential low performance years are captured for the project. Additional sensitivity considerations should be applied to FPV-specific components where there is a general lack of long-term project data available, which contributes to an overall increased uncertainty for the long-term energy prediction.

  The process for uncertainty analysis in the energy model is described in [3.9].

The energy model process is graphically represented in the flow chart in Figure 3-1.

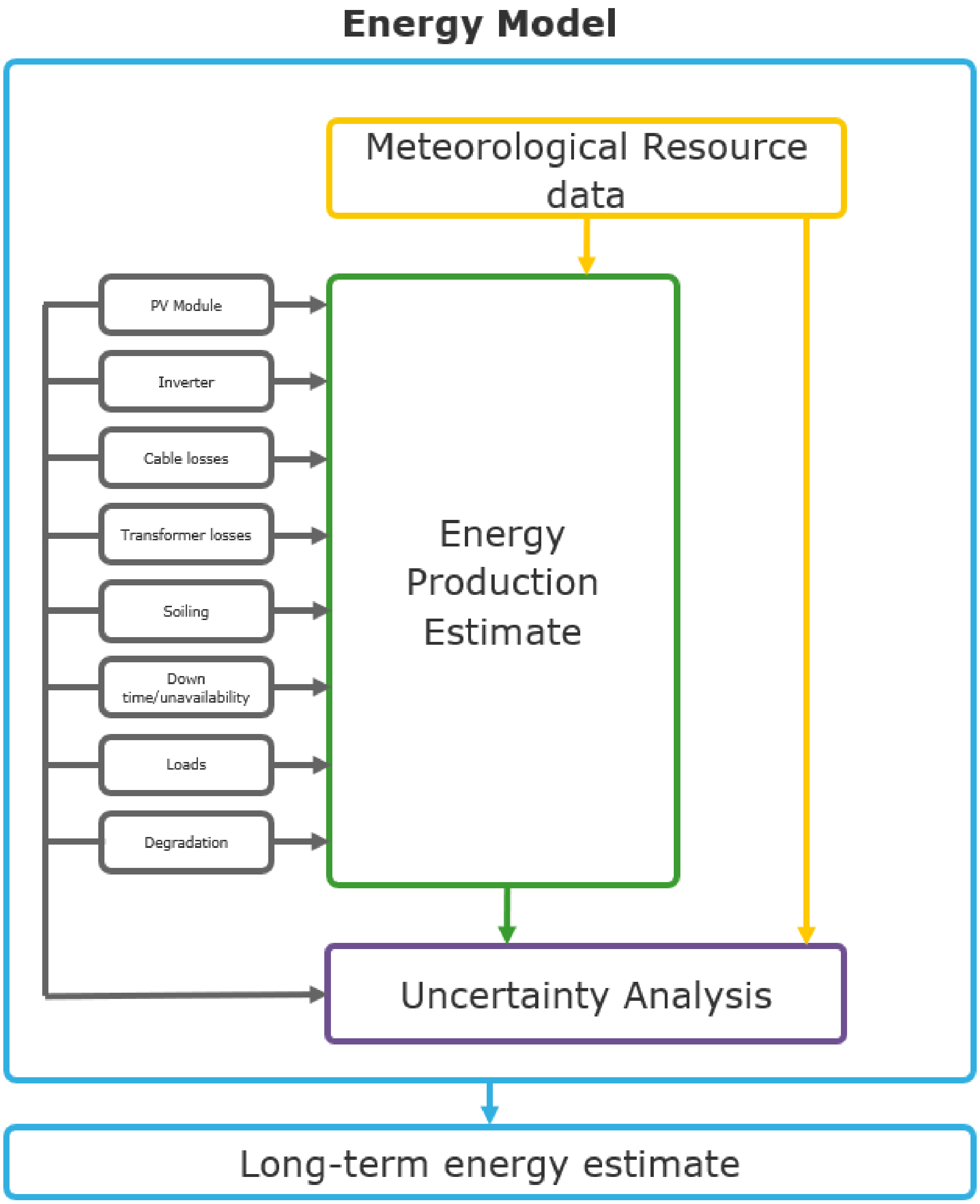

Figure 3-1 Energy model

3.2 Meteorological resource data

3.2.1 General

For the EYA, site specific and accurate meteorological resource data shall be used as input. The long-term resource data shall be time series data based on long-term satellite observations and consisting of at least GHI, DHI and ambient temperature. The dataset should have demonstrated validity through published comparison to high-quality ground measurements. Where available, on-site measurements should also be used.

The meteorological resource data should be minimum of 12 years to capture the long-term climatic effects. When a meteorological measurement station is used for the project, this should have a minimum duration of 12 months to capture the seasonal effects.

If there is a meteorological station in close proximity to the FPV system, this may be considered for inclusion in the analysis if appropriate. The quality of the meteorological station (sensor type, configuration and degree of maintenance) and its distance from the FPV system location shall be assessed in order to determine the impact on the reliability of the data. If the site is surrounded by homogenous topography and climate, this distance should not exceed 30-50 km. This distance shall be lower if the terrain is complex and/or microclimatic conditions are expected to be materially different between the location of the meteorological station and the FPV system area.

The following subsections include guidance, recommendations and requirements on reference satellite datasets, see [3.2.2], measurement instrumentation and installation, see [3.2.3], and best practises associated with data interpretation and manipulation for long-term resource estimates, see [3.2.4].

Guidance note:

The ideal source of irradiance data would be on-site ground-based measurements supplied by a solar monitoring station collecting data over a sufficient time period to capture seasonality effects (≥ 12 months) and long-term climactic conditions (≥ 12 years).

Practically speaking, ground-based measurements of more than 12 years is in most cases not available. Even in some regions that support a well-funded and maintained networks of meteorological ground stations, such as in the US or Australia, typical distances that a prospective solar farm may be in relation to a 'nearby' ground station may make them inappropriate as the primary irradiance input for modelling. Instead, the industry relies heavily upon satellite reference data to assess the meteorological conditions of a solar farm and in some circumstances, complemented with a short-term measurement campaign.

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3.2.2 Reference satellite datasets

There are different approaches for assessing long-term satellite meteorological resources. The choice of the appropriate approach shall be made depending on the location of the FPV project, as the satellite data providers have different characteristics for different regions. If on-site measurements are available for the project, a correlation of the data with long-term sources should be performed, further details in [3.2.4].

Satellite dataset selection shall be considered on a case to case basis. Several satellite datasets should be evaluated when conducting an EYA for the project and the most representative and reliable dataset for the site should be chosen. The number of available satellite datasets is dependent on the location of the project.

For FPV projects, it is especially important to evaluate multiple datasets as there is increased uncertainty for sites where water bodies form a part of the satellite image which the satellite data is interpreted from. There is also added uncertainty if the project site is in coastal areas. These additional sources of uncertainty should be included in the uncertainty analysis, further described in [3.9].

Guidance note:

Different satellite data providers have different spatial resolution, different data availability, different duration of recorded data, different measurements (irradiance, precipitation, wind speed etc.) and different uncertainty, bias and network of validation points for different global regions.

Despite each satellite dataset provider procuring the same raw data from the same satellite, each satellite dataset provider may process the data in several different ways. A consequence of this is that reliance on one single satellite dataset provider may lead to inaccuracy. In fact, one satellite dataset provider's product could be considered appropriate for a given location yet considered significantly under- or over-estimating at a different location in the same region. Given this, it must be stressed the importance of undertaking the necessary due diligence when undertaking a resource assessment at a prospective solar farm.

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3.2.3 Measurement instrumentation and installation

3.2.3.1 General

As highlighted in [3.2.2], there can be additional uncertainties associated with satellite datasets used for FPV projects. It is therefore recommended for the project to deploy a meteorological measurement station for a minimum duration of 12 months to reduce the uncertainty. High levels of data coverage are always recommended; however, if large amounts of data are deemed unusable, extra uncertainty should be considered in relation to the site measurements. Recommended tolerable ranges of data coverages can be 85% or higher, however it is highly site- and data quality-dependent.

A meteorological measurement station for FPV systems shall, as a minimum, record the following measurements:

- global horizontal irradiance (GHI) and plane of array irradiance (POA)
- wind speed and wind direction
- precipitation
- ambient temperature
- PV module temperature
- relative humidity.

In addition, the following parameters may also be measured:

- water temperature
- waves
- water current
- soiling.

If bifacial PV modules are used for the project, albedo measurements may also be considered.

For more accurate estimation of soiling losses, a soiling station may also be considered for FPV projects.

The data gathered during the measurement campaign shall be used to correct the long term satellite data using the measure correlate predict (MCP) described in [3.2.4.3].

The measurements also provide basis for determining the thermal loss factors to be used for the EYA which is described in [3.5.4].

[3.2.3.2] to [3.2.3.11] include minimum requirements for the sensors which shall be included in the meteorological measurement station.

Guidance note:

The data acquisition time step for the measurements are 5 or 10 minutes. For some parameters and for some projects, greater granularity may be more appropriate.

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3.2.3.2 Installation

The manufacturer's datasheet shall be consulted for installation of all sensors in the meteorological measurement station. Maximum distances from the data logger to the sensors shall comply with the manufacturer’s instructions. Adequate enclosures shall be ensured, taking into account site-specific conditions and according to the manufacturer’s instructions.

The measurement station shall be installed in reasonable proximity to the FPV project site. If possible, the irradiance sensors may be placed on-shore and the other sensors (wind speed, wind direction, precipitation, ambient temperature, PV module temperature, relative humidity) may be installed on a floating structure at the FPV project site on the water body. For some projects it may be considered to install a floating irradiance sensor if movement of the pyranometers are expected to be negligible. In case of on-shore measurements, care should be taken when determining a suitable location for the deployment of the solar monitoring station nearby the water body. This should include selecting a location that is likely to be climatically similar to the intended FPV project site and should take into consideration the site specific conditions which might impact the measurements representativeness of the project, such as micro climatic conditions, fog and wind blockage.

The equipment shall be installed on a suitable structure for the site and the site-specific conditions. If high winds and/or waves and/or currents are expected at the site, this should be taken into consideration in the choice and in the installation of the equipment. The pyranometers shall be unshaded, and the wind speed and wind direction measurements shall be unobstructed. Special care should be taken for the safety of the equipment when installed floating on the water body.

Wind speed and wind direction shall be measured at height similar to the planned PV modules design height, and without obstructions. Ambient temperature shall be measured at height similar to the planned PV modules design height to capture the ambient temperatures which will be observed by the PV modules.

PV module temperature sensors can be installed on project specific PV modules. PV module temperature sensors shall be placed according to the manufacturer’s instructions. If possible, the PV modules should be installed on project-specific floats to accurately determine the project’s thermal loss factors, as discussed in [3.5.4]. If the project-specific floats layout comprises multiple rows and/or multiple PV modules in series, the PV module temperature measurements may be taken at multiple points in the system to gain understanding of temperature difference between the centre and edge of the system.

Water temperature measurements shall be taken at a representative location.

Solar met station documentation, including installation reports, calibration certificates, logger settings files and maintenance records, shall be checked to verify the following:

- instrument classification, calibrations and re-calibrations (if applicable), including correct application of calibrations by the logger
- station set-up and maintenance history
- possible sources of shading to the met station
- changes to instrumentation.

The manufacturer’s manual/instructions shall be consulted for maintenance of all sensors in the meteorological measurement station.

3.2.3.3 Pyranometers

The pyranometers used as a part of the meteorological measurement station shall be class A (secondary standard) according to ISO 9060. It is recommended to have redundant sets of pyranometers.

The pyranometers shall be calibrated according to the manufacturer’s instructions and according to ISO 9846.

Guidance note:

Redundant pyranometers allow for detailed cleaning of the data to take place. Where redundant on-site measurements are not available, it can be difficult to pick up on the more subtle issues that can affect irradiance data (e.g. slight changes to the expected irradiance profile caused by soiling, condensation or alignment/tilt errors). The reference datasets may be used in the cleaning process, but do not provide the same level of resolution or accuracy and therefore limit the extent to which problems can be identified.

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3.2.3.4 Wind speed and wind direction

For wind speed and wind direction measurements, cup anemometer and wind vane or ultrasonic wind sensor should be used.

If a wind vane and cup anemometer is used for the meteorological measurement station, this shall be class 1 according to IEC 61400-12-1.

If an ultrasonic wind sensor is used, it shall be validated by an independent third party.

The components should be site specific and consideration should be taken to predict the maximum wind speed observed at the site and to choose a wind speed measurement device with sufficient rated maximum wind speed.

The wind speed measurements shall adhere to the following minimum requirements:

— Measuring range: 0 m/s to 60 m/s (or maximum expected wind speed at the site)
— Resolution: 0.1 m/s
— Accuracy: ± 3%.

Wind direction measurements shall adhere to the following minimum requirements:

— Measuring range: 0° to 359.9°
— Accuracy: ± 3%.

Wind gusts shall be measured at minimum 3 second intervals.

3.2.3.5 Precipitation

Precipitation shall be measured with weighing precipitation sensor, tipping bucket rain gauge, radar or similar measuring equipment. The precipitation measurements shall adhere to the following minimum requirements:

— Resolution: 0.3 mm
— Accuracy: < 5%
— Maximum intensity: according to the site historic precipitation data.

3.2.3.6 Ambient temperature measurements

The ambient temperature sensors shall be shielded from direct sunlight by a radiation shield. The ambient temperature measurements shall adhere to the following minimum requirements:

— Measuring range: -40°C to 60°C
— Accuracy: ± 0.3°C.

3.2.3.7 PV module temperature measurement

PV module temperature sensors should be resistance thermometers or thermocouples (for example PT100 or PT1000) and/or modbus components. Thermocouples shall comply to IEC 60584, resistance thermometers shall comply to IEC 60751. The PV module temperature measurements shall adhere to the following minimum requirements:

— Measuring range: -40°C to 150°C
— Accuracy: class B.

3.2.3.8 Relative humidity

Relative humidity should be measured with a capacitive sensor. The relative humidity measurements shall adhere to the following minimum requirements:

— Measuring range: 0-100%
— Accuracy: ± 3%.

3.2.3.9 Water temperature measurement

For water temperature measurements, water temperature probes should be used. Water temperature measurements should be taken at 1 m below water surface or shallower. The sensors should be resistance thermometers or thermocouples (PT100, PT1000) and/or modbus components. The sensors should be appropriate for the site. If the installation is in a saline environment, chosen sensors shall be designed for saline environment. The water temperature measurements shall adhere to the following minimum requirements:

- Measuring range: -5°C to 70°C
- Accuracy: ± 0.15°C.

3.2.3.10 Waves & current

For wave and current measurements considerations, see [2.3] and [2.4] respectively. The measurements should as a minimum provide enough accuracy to determine the change in tilt angle and/or azimuth observed by the PV module caused by waves and/or currents which will affect the global in-plane irradiance.

3.2.3.11 Soiling station

A soiling station should be installed for FPV project sites where the FPV system is expected to be exposed to significant dust soiling and/or bird droppings, in particular if planned to be left unattended for long periods during the operational phase.

Guidance note:

A typical soiling monitoring station comprises of at least two PV modules, where each PV module is maintained in a short circuit across a 20 Amps (A) shunt to measure the short circuit current. One PV module function as the 'clean module' which is manually cleaned at a site-specific frequency. The second PV module functions as the 'control module', which does not receive manual cleaning and is only subject to a clean when a rain event occurs.

The soiling monitoring station primarily measures the difference in electrical current between the two PV modules. As soiling gradually accumulates on both modules the electrical current is reduced. When the 'clean' module receives a manual wash, the output of the PV module will return to nominal. The 'control' PV module will however continue to accumulate soiling and hence lowered output/current until a rain event occurs.

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3.2.4 Data interpretation and modelling

3.2.4.1 General

When on-site measurements are used in the EYA, processing and appropriate implementation of the raw data shall be conducted.

3.2.4.2 On-site measurements data cleaning and processing

The filtering process for the on-site measurements shall follow the filtering guideline in IEC TS 61724-3:2016, Table 3 or similar guidelines. The data filtering should be adapted to the site-specific conditions.

Any data identified as erroneous shall be removed. However, if the issues are subtle and/or affects large amounts of data, all of the affected data is not possible/feasible to remove. In this case, extra uncertainty should be considered in relation to the measurements in the uncertainty analysis described in [3.9].

Guidance note:

Irradiance data is subject to regular fluctuations throughout the day due to cloud cover. Such fluctuations are seen almost uniformly across all the instruments at a site, unless there is an appreciable distance between some of the instruments. Any problems with the data are most obvious on clear days and tend to affect only one instrument or multiple instruments in a non-uniform manner.

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3.2.4.3 Measure-correlate-predict analysis

When a short-term on-site measurement of minimum 12 months is available, this should be used to adjust the long-term satellite reference data by correlating the on-site measurements over a concurrent period of time with the long-term reference; this procedure is commonly known as the measure-correlate-predict (MCP) methodology. The final data product of the MCP technique may be either an 8760 typical meteorological year (TMY) or a full time series which equate to the long-term meteorological estimates provided under the MCP method. Both methods are satisfactory for determining long-term energy yield.

However, as generation of a TMY may result in loss of information, the use of full timeseries is recommended, where possible.

Guidance note:

As discussed in [3.2.2], using only long-term satellite reference data leads to risk of introducing bias that can be significant and vary depending on the site. Conversely, on-site data campaigns have typical durations much lower than the acceptable minimum long-term reference data source requirement (i.e. 12 years or longer). In order to overcome this issue, a common method within the industry is to combine long term satellite reference data with a duration of short-term measurement campaigns using the measure-correlate-predict (MCP) methodology. In implementing this approach, solar irradiance data measured at site is used to adjust satellite reference data by correlating the on-site measurements over a concurrent period of time with the long-term reference. The purpose of the correlation adjustment is to improve the quality of the reference GHI time series by reducing bias and ultimately the overall uncertainty in the resource data.

For each parameter (i.e. GHI, Temperature, wind speed and DHI if possible), long term correlations are typically performed between the site and reference sources on the following correlation periods:

- daily correlation grouped by months
- 10-day averages
- monthly average. Should only be used if a significant number of months are available and the data coverage is above 80%-90%.

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3.2.4.4 Recommended measurement campaign duration

If on-site measurement campaign is performed, the minimum duration of the on-site measurements used to perform the MCP shall be one (1) concurrent year with the reference satellite data. The on-site measurements shall also be 12 consecutive months to capture the seasonal effects of the meteorological resources of the site and the microclimatic conditions.

Guidance note:

Sometimes projects are in geographical areas with more seasonal bias conditions than other areas (e.g. tropical sites), so an annual seasonal variation may not be fully captured in the correlation if less than 12 months of consecutive data is available.

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3.3 Energy production estimate

3.3.1 General

The energy production estimate is the processing of data within the energy model, i.e. combining the meteorological resource data with losses assumptions and estimations, within the energy simulation software. The data resulting from the resource evaluation of the project should be used as input in the energy simulation software.

For the EYA to accurately predict the energy production of the project, the components used and/or intended to be used for the project such as inverters, PV modules, transformers and floats shall be modelled in the energy production estimate. The energy production estimate shall also include FPV project layout, system design, cable lengths and the grid interconnection point.

For FPV projects particular attention should be given to the types of floats used, and how this will impact the FPV system’s wave-induced mismatch losses and the thermal loss factors.

[3.3.2] and [3.3.3] include description of the component inputs to the energy production estimate and [3.4] to [3.7] include description of different loss factors and recommendations on how these can be represented in the energy production estimate. The loss factors are sorted into the categories: optical losses, PV module losses, inverter losses and electrical losses. Other losses and consideration are included in [3.8].

3.3.2 PV module files

The PV module PAN file used in the energy simulation shall match the PV modules which is intended to be used for the FPV system. The PAN files shall adhere to standard industry practices for PAN file creation.

As a minimum, PAN files should be created applying data from the PV module manufacturer’s data sheet. For better accuracy, datasheet, test results and measurement data provided by the manufacturer should be used (e.g. flash-test data, low light performance data and LID test results). As best practice, datasheet and third-party test results and measurements should be included.

3.3.3 Inverter files

The inverter OND file used in the energy simulation shall match the inverters which is intended to be used for the FPV system. The OND files shall adhere to standard industry practices for OND file creation.

As a minimum, OND files should be created applying data from the inverter manufacturer’s data sheet. For better accuracy, datasheet and efficiency curves provided by the manufacturer should be used. As best practice, datasheet and third-party test results and measurements should be included.

3.4 Optical losses

3.4.1 General

Optical losses are in this RP defined as energy losses resulting from reduced irradiance in the plane of array for the FPV system. Optical losses assessment shall include:

- incidence angle modifier losses
- near shading losses
- far shading losses
- soiling losses.

3.4.2 Incidence angle modifier losses

Incidence angle modifier (IAM) losses are losses due the fraction of the incident light that is lost due to reflection. IAM loss considerations shall follow standard industry practices for IAM losses. It is recommended to base IAM profiles on third party test reports. If third part test reports are not available, a theoretical modelling approach may be applied. The theoretical model should take into consideration PV module anti-reflective coating, if present.

Guidance note:

The IAM factor is sensitive to any anti-reflective treatments that may have been employed during manufacturing, and those effects are typically incorporated into the PV module file. For most crystalline PV modules, the IAM behaviour is specified through the ASHRAE model with a value called b0. For example, energy simulation software usually applies the b0 value based on the Fresnel optical transmission law (ASHRAE model) for a single layer of standard glass in contact with the solar cell.

The ASHRAE model yields a theoretical IAM profile which approximates the reflective behaviour of a PV module. In practice, each PV module type or family may have its own unique, customized IAM profile.

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3.4.3 Near shading losses

Near shading denotes objects which cause smaller localised shadows that will affect the FPV system performance. Near shading loss considerations shall follow standard industry practices for near shading losses.

The shading losses shall take into consideration shading objects in and around the FPV system in a 3D modelling tool. These shading items may be transformer stations, maintenance buildings, inverters, trees and over-head transmission lines. When no shading objects are present, a 2D modelling approach can be applied.

The near shading model shall account for the PV module characteristics (e.g. number of bypass diodes), electrical configuration and orientation of the PV modules and the system.

3.4.4 Far shading

Far shading denotes objects which obstruct the horizon observed by the FPV system. Far-shading loss considerations shall follow standard industry practices for far-shading losses. The far losses shall be taken into considerations by defining the horizon line in the energy simulation software, either through import of a project specific horizon line, use of horizon tools or calculating the horizon line for the project.

3.4.5 Soiling losses

Soiling losses occur when snow, dust or light-blocking material accumulates on the PV modules and reduce the incident irradiance on the PV module(s). Soiling loss considerations shall follow standard industry practices for soiling losses, with additional considerations for FPV. FPV systems may be subject to increased soiling losses due to bird droppings and increased soiling losses due to biofouling.

Past project experience, engineering judgment and use of available historical data should be used to pragmatically assume the soiling losses. When available, data gathered from the meteorological measurement station soiling sensors and/or precipitation measurements should be used to create a project soiling profile. Planned yearly PV module washes should be used as input when determining the projects soiling profile as described in [9.3.2.2].

Site-specific characteristics for the project impacting the soiling losses shall be considered on a project basis, including, but not limited to, presence of dust and/or air pollution in the area, seasonal pollen, humidity, effect of water spray.

For projects in areas with resident and/or migratory birds, the historical records of presence and migrations of birds may be used in determining when the FPV plant is more likely to observe increased soiling from bird droppings. In some cases, bird repellent measures may be considered to reduce soiling from bird droppings as mentioned in [9.3.2.2].

Biofouling may be expected for some FPV projects, especially in tropical areas or in nutritious waters such as irrigation ponds, ponds with run-off from farmland or ponds with surrounding forest. This shall be properly assessed as it can contribute to soiling losses or near-shading losses where plants grow on the FPV array. Historical imagery of the project site may be used to assess the seasonal growth trends of water plants (such as water hyacinth).

Snow losses shall be considered for FPV systems in project locations with snow fall. The snow losses may be greater for FPV systems as the PV modules are close to the supporting structure and when the snow depth increases this may cover the PV modules. Freezing water bodies and snow accretion leading to potential snowdrift on the floating structures shall also be taken into consideration, especially if the project site is windy.

Guidance note:

Dust soiling and snow losses are dependent on historical precipitation levels, system orientation, PV module wash frequency, and the accumulation rate of dust, debris, and snow. The accumulation rate of particulates is site-specific and can be influenced by factors such the type of soil, moisture content, proximity to highways or farmland, biofouling and the prevalence of bird droppings. FPV systems have been observed to be subject to considerable soiling due to bird droppings, especially in the external rows of the FPV array. This soiling can contribute to the losses considerably. In some FPV projects it has also been observed less dust soiling as the dust will not be carried to the FPV system by the wind – depending on the FPV systems distance from shore.

Steep tilt angles also allow accumulated snow to more easily slide off a PV module.

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3.5 PV module losses

3.5.1 General

PV module losses are in this RP defined as energy losses resulting from PV module performance reduction as a function of irradiance, temperature and degradation. PV module losses assessment shall include:

- low-light losses
- PV module quality losses
- light-induced degradation
- temperature loss factors.

3.5.2 Low-light loss

Low-light loss is the difference in performance for the PV modules when the irradiance is lower than standard testing conditions (STC). Low-light loss considerations shall follow standard industry practices for low-light losses.

As a minimum, low-light losses values from the PV module datasheet should be used or, if no values are given, project experience and/or engineering judgement can be applied. For better accuracy, low-light performance of the PV modules provided by the PV module manufacturer should be used. As best practice measured data provided by a third-party testing agency should be used.

3.5.3 PV module quality factor

The PV module quality factor (MQF) is a user-defined generic loss factor used to account for miscellaneous losses, and it may be either positive (loss) or negative (gain). The following three adjustments should be included in the MQF calculation: nameplate bias (loss/gain), maximum power point tracking loss, and modelling bias (loss/gain). MQF considerations shall follow standard industry practices for determining MQF.

Guidance note:

PV module datasheets quote a power tolerance window in which the actual power rating of a given PV module is expected to reside. Often, the quoted power tolerance window is 'positive', indicating that the actual power rating of the PV module will at least be equal to, but may exceed, the nameplate rating. These power tolerance windows are expressed both in terms of percentages (e.g. 0 to +3%) and wattages (e.g. 0 to +5 W). In the absence of flash test data, it is unknown where the lot average of a group of PV modules will be centred within a quoted power tolerance window. It can then be assumed that the distribution is centred at the lower quartile of this window.

To ensure that the most accurate inputs are used in the MQF and production simulation, flash test data from the manufacturer can assist in order to determine the actual nameplate bias for delivered PV modules.

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3.5.4 Temperature loss factors

3.5.4.1 General

The temperature coefficient of power for a given PV module defines how the PV module output power will respond to changes in PV module temperature. PV module datasheets detail the temperature coefficient of power for a class of PV modules and shall be included in the PAN file, see [3.3.2]. Thermal loss factors indicate how changes in temperature and wind speed will affect cell temperatures. Temperature loss is calculated in the energy production estimate using the technical specifications of the PV module and the thermal loss factor inputs.

3.5.4.2 Cooling effect

It is recommended to apply different thermal loss factors for different types of systems and different float technologies. Systems which allow for more free-flowing air to circulate around the PV modules (higher thermal loss factors) will dissipate more heat and experience lower temperature losses.

In the absence of appropriate simulation software to model the physical phenomena governing cooling effects observed by the FPV system, which includes potential increased cooling from water and wind speed and wind direction, the best practice procedure to determine the thermal loss factors for FPV systems is through application of technology-specific measurements. Key aspects which shall be quantified and included in a measurement campaign to determine the characteristic thermal loss factors for an FPV system are:

— plane of array irradiance
— ambient temperature
— wind speed
— PV module temperature.

The minimum recommended duration of the measurements is one year, see [3.2.4.4] for details on measurement campaigns.

Water temperature measurements may be considered, as this can provide valuable input to evaluating the thermal loss factors, and may be used as input, instead of or together with the ambient temperature, when calculating the expected cooling effect for the system.

3.5.4.3 Thermal loss factor equations

After completion of the measurement campaign, the thermal loss factor U, in [W/m²K] may be calculated using the following equation:

$$U = \frac{\alpha \times G_{inc} \times (1-\eta)}{(T_{cell} - T_{amb})} \tag{3.1}$$

Where
T_{cell} = cell temperature [°C]
T_{amb} = ambient temperature [°C], acc. to the meteorological data
G_{inc} = irradiance on the PV module or FPV array [W/m²]
α = the absorption coefficient of solar irradiation, i.e. (1 for full absorption) []
η = PV module efficiency [%].

The typical value of the absorption coefficient α is approximately 0.9. This shall be adjusted to the actual PV module characteristics.

A correction factor may be applied to the PV module temperature measurements to estimate cell temperature, based on information provided by the PV module manufacturer or relevant research.

The thermal loss factor U may be split into a constant component U_C and a factor proportional to the wind velocity factor U_V using equation below:

$$U = Uc + Uv \times v \tag{3.2}$$

Where v [m/s] is the wind velocity.

The values for U_C and U_V are found by linear regression analysis of U versus v. Once calculated, U_C and U_V should be implemented in the energy model to simulate temperature losses.

In cases where PV module temperature measurements are not available, an approach using relevant literature may be considered, such as the approach in Kamuyu et al. (2018). The approach on how the literature is applied to determine the PV module temperature shall be carefully considered, justified and documented.

Wind direction shall be considered, as this may have an impact on the cooling effect, where a beneficial wind direction can contribute to increased air circulation and dissipation of heat. Relevant research, project experience and/or engineering judgement should be applied when considering this effect.

Relevant research, engineering judgement and/or project experience should be applied to consider the temperature difference between the edge and centre of the floating PV system as PV modules on the edge of the system tend to be more exposed to wind cooling.

Water temperature is currently not included in most energy production estimates, but it can affect the PV module operating temperature. Incorporating water temperature into the energy production estimate could therefore increase its accuracy.

For some floating PV technologies, such as 'membranes' defined in [5.2.8.1], the use of water temperature miay be considered as an alternative input instead of the ambient temperature as the technology may have more direct contact with water. This approach, if used, shall be justified, documented and validated with relevant research and/or project experience. The study provided in Selj et al. (2019) may be used as guidance to understand the relationship between water temperature and cell operating temperature.

In cases where accurate wind speed is not available for the project site, using U_V as a factor in the energy simulation may give an inaccurate result. Alternative approaches to combine U_V with U_C may be considered, and properly justified and documented.

3.5.4.4 Engineering judgement

In the absence of on-site measurements, the thermal loss factors should be sourced from third-party literature, such as relevant research and white papers. The selection procedure for the thermal loss factors shall be documented and subject to engineering judgement.

The selection procedure should include a qualitative comparison between the design of the chosen FPV array and the FPV array object of study in the pertaining literature. When a range of thermal loss factors is provided in the study, engineering judgement should be used to determine which value within the range should be considered. When evaluating the appropriate thermal loss factors for the technology, the following shall be considered as a minimum:

- type of FPV array, as defined in [5.2.8.1]
- level of air circulation below the PV modules
- degree of contact with water of the floats supporting the PV modules
- material and thermal behaviour of the floats
- size of FPV system
- layout of FPV array.

The selection methodology of thermal loss factors shall be carefully considered, justified and documented.

The selection of appropriate thermal loss factors shall be done on a case by case basis, where also the site-specific conditions, such as water depth, currents, wind speed and other environmental conditions shall be taken into consideration. It is recommended that the literature references used as basis for the selected thermal loss factors refer to a similar climate as the FPV project site.

If the project is in the development phase and the FPV project encompasses monitoring of the parameters outlined in [3.5.4.2] during the operational phase, these measurements may be used to update the EYA with accurate thermal loss factors when sufficient data is available.

Guidance note:

While projects normally experience reduced power output due to the ambient temperatures being higher than STC, the local meteorological conditions may result in energy output above nameplate rating for the PV modules if the ambient temperature is lower than STC throughout the year, while the irradiance is at STC or higher.

In both land-based and FPV systems, passive PV module cooling is affected by the design of the system. A spacious and ‘open’ system will improve air circulation, and thus enhance the cooling effect on the PV modules. Both the wind speed and direction play an important role in this. Winds hitting the PV modules from the front provide less cooling than wind blowing in from the sides or the rear side of the PV modules. In FPV systems, the cooling effect may also be affected by the size and material of the floats, and the footprint (coverage ratio) of the system on the water surface. The type of floating system defined as 'Pure floats' in [5.2.8.1] can be considered as 'large footprint and closed structure' and the type of floating system defined as 'Floats with framework' in [5.2.8.1] can be considered as 'small footprint and open structure'. Thermal loss factors may therefore vary substantially between technologies. Dörenkämper et. al. (2021) reports thermal loss factors U in the range of 36-37 W/m²K for 'large footprint and closed structure', 55 – 57 W/m²K for 'small footprint/free standing and open structure' and 41 W/m²K for 'medium footprint and closed structure', and FPV systems. This and other similar studies can be used as guidance for selecting appropriate thermal loss factors. Liu et al. (2018) may also be consulted for different U values.

Tests performed on FPV systems with included active water cooling, such as sprinklers, have shown an energy gain of up to 10% due to cooling effect (Rosa-Clot and Tina (2020), Cazzaniga et al. (2018)).

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3.5.5 LID losses

Light-induced degradation (LID) occurs in the first few hours of exposure to sunlight and irreversibly reduces the solar conversion efficiency of a crystalline PV module. LID losses considerations shall follow standard industry practices for LID losses. As a minimum, assumptions based on project experience and/or engineering judgement for LID losses should be included. For better accuracy, measured LID data provided by the manufacturer should be used. As best practice, measured LID data for the PV modules based on third-party test results should be included.

3.6 Inverter losses

In this RP, inverter losses are defined as energy losses to inverter performance and inverter characteristics.

Inverter losses include:

- inverter clipping
- losses due to power threshold
- losses due to voltage over nominal inverter voltage
- losses due to voltage threshold
- inverter night consumption.

Inverter loss considerations shall follow standard industry practices for inverter losses.

For specific projects, with temperature ranges outside rated temperature for the inverter, altitude higher than rated altitude and where the inverter is used to limit the power output of the system (e.g. due to grid limitations) temperature, voltage, or power derating (i.e. limitations) shall be applied to the energy model.

3.7 Electrical losses

3.7.1 General

Electrical losses are in this RP defined as energy losses resulting from sub-optimal electrical behaviour of the FPV system. Electrical losses assessment shall include:

- mismatch losses
- direct current and alternating current cabling losses for systems using central inverters

- direct current and alternating current cabling losses for systems using string inverters
- transformer losses.

3.7.2 Mismatch losses

3.7.2.1 General

Types of electrical mismatch in a PV system are voltage mismatch and current mismatch.

There are four main factors that affect mismatch in FPV systems:

- PV module mismatch (differences in each PV module's voltage and current)
- wire run mismatch (voltage mismatch from different length wire runs)
- soiling mismatch (varying levels of dust or snow on each PV module will cause more total mismatch than a rainy location where PV modules are more uniformly clean)
- wave-induced mismatch (mismatch losses due to wave movement of the FPV system).

PV module mismatch, wire run mismatch and soiling mismatch loss considerations shall follow standard industry practices. Wave-induced mismatch losses due to movement of the FPV system caused by waves needs further consideration.

3.7.2.2 Wave-induced mismatch

For FPV systems, string mismatch and PV module mismatch due to float motions from waves and water current shall be considered. Wave-induced mismatch will occur when the PV modules in one string or multiple strings connected to one inverter are tilted at different angles and/or oriented at different azimuths due to wave movement. Changing the tilt angle and/or azimuth will affect the global in-plane irradiance observed by the PV module. As a result, each PV module in the string may exhibit different voltage and current characteristics, and thereby introduce an additional mismatch loss.

As a general guideline, if engineering judgement supports the assumption that the wave, wind and current conditions observed at a specific FPV site will contribute to additional string mismatch losses, an appropriate amount of losses should be included in the energy model.

The floating technology used for the project should be carefully considered. Rigidity of the floating structure, mooring and anchoring solution, size of PV islands and float interconnection will have an impact on the wave-induced mismatch losses. The following factors will indicate difference for wave-induced mismatch losses for float technologies:

- single body float vs. multi-body float
- pure float vs raft
- steel vs plastic float interconnection
- solid vs flexible float interconnection.

When determining wave-induced mismatch losses for the project the following environmental factors, described in Sec.2, shall be considered:

- wave height
- wave frequency
- wave direction
- wind speed
- wind direction
- current speed
- current direction.

Wave tank measurements

If available, wave tank measurements and the measured floats motions at different wave and/or current conditions may be used to estimate the wave-induced mismatch losses. The motion of the FPV system can be extrapolated from the wave tank measurements to represent the wave and/or current characteristics of the FPV project site. Guidance on model testing in wave tanks is provided in [4.5.5.2].

Numerical analysis

If wave tank measurements are not available, the motions of the floating structure relevant for the project site can be established by numerical analysis. See guidance in [4.5].

The boundary element model (BEM) can be used to determine response amplitude operator (RAO) for the float type. From the RAO for the float technology, the movement of the floats due to the waves and current can be determined. From this the mismatch losses can be estimated.

Engineering judgement

If neither wave tank measurements, CFD or BEM/RAO analysis is available, engineering judgement based on the wave, wind and/or current conditions observed and/or calculated for the project site and the floating technology characteristics should be considered to estimate the movement of the floating PV system. The following aspects, as a minimum, shall be considered while assessing the movement due to waves for the different float technologies:

— float configuration
— number of PV modules per float
— float weight
— FPV array size
— types of interconnection between floats
— foat material
— string interconnection scheme.

Guidance note:

Dörenkämper et. al. (2019) contains useful guideline for wave-induced mismatch losses. FPV array types, see [5.2.8.1], that allow for greater freedom of relative movement between neighbouring floats and between different PV modules within the same string are considered to be more prone to higher wave-induced mismatch losses.

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Inclusion of wave-induced mismatch in the energy simulation software

Modelling software may be used to gain a preliminary understanding of the mismatch losses incurred between PV modules due to relative wave-induced movement in the FPV system.

As discussed previously, wave induced mismatch losses may occur when the PV modules in one string or multiple strings connected to one inverter are tilted at different angles and/or oriented at different azimuths. It can be expected that each PV module on a string within an FPV system will be to some degree off-tilt relatively to adjacent PV modules on that string. The power output of a string will be limited by the PV module with the most unfavourable tilt-azimuth combination on that string. In this sense, when trying to understand the overall mismatch loss due to relative wave motion, the power output of the PV module with the most unfavourable tilt-azimuth combination on a string should be considered.

In order to understand the mismatch losses incurred when a PV module or string of PV modules are positioned at different relative angles, it is recommended to run a batch of simulations varying the azimuth and tilt over a given interval to gain an understanding of how the system may respond to different magnitudes of wave motion.

Rigidity of the structure, mooring and anchoring solution may have an impact on the expected change in PV module angle due to wave motions. This may have the effect of reducing or increasing the wave-induced mismatch losses. As floating structure size (single body or multi-body) and float connection types (steel/plastic and flexible/solid) may have material impact on wave-induced mismatch, additional care should be taken when assessing wave-induced mismatch on annual energy estimates.

Calculation example may be found in App.A.

Guidance note:

Voltage mismatch occurs when multiple conductors, operating in parallel, are forced to operate at a common 'compromise' voltage at the inverter bus. This loss is usually minor to negligible, unless the series strings being connected in parallel do not contain the same number and type of PV modules in series, or are otherwise compromised as a result of bypass diodes being activated.

Current mismatch occurs when non-alike PV modules are connected in series, and to some degree, all PV modules are non-alike, either as a result of manufacturing or as a result of receiving different levels of irradiance. Weak PV modules will essentially restrict the amount of current that can flow through the series string, again in an electrical 'compromise', the effect of which is a reduction in power that is normally more significant than voltage mismatch.

This loss will be different depending on which inverter technology is being used for the project, multiple MPPT inverters, smart MPPT inverters, string inverters or central inverters will observe different impact of wave-induced mismatch loss.

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3.7.3 DC cable losses

DC cable loss considerations shall follow standard industry practices for DC cable losses. The losses shall be calculated based on the total wire length for the project. If detailed cable schedules and drawings are not provided, engineering experience can be applied to assume an appropriate loss at STC for central inverters and string inverters.

For FPV systems, consideration of cable losses should be taken when determining inverter installation location. In larger FPV arrays, land-based inverters (for central inverter based systems) and land-based first level step up transformers (for string inverter based systems) may contribute to considerable cable losses – depending on the distance from the PV islands to shore.

3.7.4 AC cable losses

AC Cable loss considerations shall follow standard industry practices for AC cable losses. The losses shall be calculated based on the total cable length for the project. If detailed cable schedules and drawings are not provided, engineering experience can be applied to assume an appropriate loss at STC for central inverters and string inverters.

For FPV systems, consideration of cable losses should be taken when determining inverter installation location. In larger solar farms land-based inverters (for central inverter based systems) and land-based first level step up transformers (for string inverter based systems) may contribute to considerable cable losses – depending on the on the distance from the PV islands to shore, distance to the grid interconnection point and solar farm metering arrangement.

3.7.5 Transformer losses

Transformer losses are fixed and variable losses associated with the operation of the transformer. Transformer loss considerations for medium and high voltage (MV, HV) shall follow standard industry practices for transformer losses.

3.8 Other losses and considerations

3.8.1 General

Other considerations and miscellaneous losses for the FPV system should include:

- bifacial PV modules considerations
- solar farm downtime and unavailability losses
- plant station load losses
- system degradation
- trackers considerations

— grid limitations.

3.8.2 Bifacial PV modules considerations

Bifacial modelling shall follow standard industry practices for calculating the energy including bifacial gain. If on-site measurements of albedo are not available for the project, satellite data or relevant research can be used.

The aperture ratio and ground coverage ratio are typically high for FPV systems, depending on the type of FPV array and type of floats. This shall be considered when modelling an FPV system with bifacial PV modules. The structural shading losses and rear-side mismatch losses shall be calculated based on engineering drawings of the FPV array.

3.8.3 Down time and unavailability losses

Down time and unavailability loss considerations shall follow standard industry practice for down time and unavailability losses.

Some FPV systems might be located on water bodies with large water level variation and the FPV system might become stranded at times during the year. The times when the FPV system is stranded may be considered as down time or unavailability, depending on the FPV system design and its suitability for stranded operation.

3.8.4 Plant station load loss

Plant station loads which should be included in the EYA include internal loads for the project which are not separately metered and billed. Examples include loads associated with monitoring equipment, grounding transformers, inverter stations, substations, active cooling, tracking mechanisms, O&M facilities and CCTV. Plant station load loss considerations shall follow standard industry practice for plant station load losses.

Guidance note:

The extent of this loss is dependent on the climate, system capacity, and other project characteristics. For example, an inverter with heater will have higher energy consumption compared to an inverter in a warmer climate. Energy consumption in association with O&M facilities are also expected to be higher in colder climates.

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3.8.5 System degradation

System degradation considerations shall follow standard industry practice for system degradation. Currently there is limited long-term data available for FPV performance, when sufficient long-term data is available, it might be relevant to apply a different degradation methodology compared to ground-mounted PV. If on-site data has been collected and project experience is available, this can be applied to the EYA. Engineering judgement, relevant research and/or project experience can be applied to adjust the degradation rates for FPV systems. The methodology for the adjustment shall be justified and documented.

Guidance note:

Long-term degradation is a slow and irreversible decline of a PV module’s power output. A system degradation rate, as opposed to a PV module-only degradation rate, includes the cumulative effects of differing degradation rates among individual PV modules and the system-level mismatch that ensues from that diverging mix of declining PV modules. In roughly a “weakest link” manner, the most rapidly degrading PV modules exert a collective dragging down of performance at the system level.

DNV GL has conducted an extensive review of PV degradation rates, including the review of 135 papers on this topic in association with the National Renewable Energy Laboratory (NREL). This work indicates that half of crystalline PV system annual degradation rates vary within the interquartile range of 0.2% - 1.2% for systems that deploy multi-crystalline PV modules. Given that the range of this rate is of similar magnitude to the rate itself, there is a high level of uncertainty associated with any presumed single value of degradation. The white paper RANA-WP-03-A summarises this study.

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3.8.6 Trackers

When trackers are used in FPV projects, increased plane of array irradiance due to use of trackers shall follow standard industry practices.

3.8.7 Grid limitations

Grid limitations can be both power limitations at the grid interconnection point and/or limitations due to grid curtailment, which will result in a reduction of energy output for the facility. In some cases, this can depend on the location of the energy metering of the FPV system. If the grid limitation has impact on the projects energy export this shall be included in the EYA.

3.9 Uncertainty analysis

3.9.1 General

EYA for FPV systems shall include an uncertainty analysis. The uncertainty analysis shall include as a minimum:

— resource uncertainty (for satellite data and on-site measurements, [3.9.2])
— solar resource variability (yearly variability for irradiance [3.9.3])
— soiling variability (yearly variability for soiling, [3.9.4])
— model uncertainty (uncertainty for model inputs, [3.9.5])
— additional FPV uncertainties (sensitivity analysis of FPV specific attributes [3.9.6]).

The uncertainty should as a minimum provide P(50), P(75) and P(90) energy projections for minimum 1-year, 10-years and project lifetime. The energy projections shall include system degradation, as detailed in [3.8.5], from year 2 until project end of life.

FPV systems shall follow industry standard practices when considering project uncertainty, with additional considerations for aspects of resource uncertainty and modelling uncertainty discussed in [3.9.2] and [3.9.5].

Guidance note:

The common goal in developing a projection of future energy production for a PV system is to estimate the long-term average. Uncertainty in energy projections is normally a concern when the actual production is noticeably lower than the long-term average projection.

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3.9.2 Resource uncertainty, long-term satellite datasets and on-site measurements

Solar resource uncertainty denotes the potential deviation of the assumed annual GHI from the true long-term average the annual GHI. The satellite data providers typically have documented uncertainty and bias associated with the satellite data though validation studies. This should be included in the solar resource uncertainty.

If on-site measurements have been collected, this data may be used to adjust the long-term satellite resource, see [3.2.4.3] for the MCP process. When on-site measurements are used in combination with long-term satellite resource, this may increase the accuracy of the assessment. The specifications of the pyranometers, temperature measurements and wind speed measurements should be considered when determining the overall uncertainty for the on-site measurements. Information for sensor uncertainty can typically be found in the sensor/equipment datasheets or be provided by the manufacturer.

Solar resource satellite data has been observed to misrepresent near-shore and on-water irradiance data. For FPV projects, this should be taken into consideration for the resource uncertainty of the project. The additional uncertainty for the project site should be acquired from the satellite data provider. If no data is available, engineering judgment and/or project experience should be applied to pragmatically assume an appropriate degree of uncertainty.

Guidance note:

For FPV projects, one may compare the satellite data for the site to a near land location (for example 1 km from the project water surface). If abnormalities and inconsistencies are detected, this can give a good indication of the degree of additional uncertainty for the project's solar resource. In some cases, it might be more accurate to apply near land satellite data.

Since part of the uncertainty in the GHI measurements is expected to be random (the true irradiance could be either higher or lower than the measurement), the uncertainty around the annual GHI total is expected to be lower than the sum of the hourly uncertainties. The hourly values can be scaled accordingly to produce an annual GHI uncertainty. A log-normal distribution can be assumed for the solar resource uncertainty. Since uncertainty is how far off the original one-year model is from true long-term average, there is no reduction in the uncertainty over time.

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3.9.3 Solar resource variability

Solar resource variability is calculated using long-term historical irradiance. Solar resource variability represents how much the irradiance differs from its long-term average. When assessing variability, multiple years of historical irradiance data should be taken to build a probability distribution, expressing it as a percentage of the long-term annual average irradiance in the typical meteorological year (TMY) used in the energy estimate.

A minimum of 10 years should be used for appropriate interannual variability calculations, while 15 years is recommended. Either a normal distribution or a Kernel estimate can be used to draw a custom probability distribution around the annual data points. The probabilities should be input into the overall analysis.

Guidance note:

The data for this calculation is typically obtained from the same database and location as was used in the energy estimate and may be estimated considering multiple years provided by a satellite data resource. The solar resource downside is worse in a single year than it is over several years, since over several years, high and low solar resource years will partially compensate for each other. Over long periods of time, the average solar resource approaches the long-term behaviour, and the solar resource variability is reduced to zero.

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3.9.4 Soiling loss variability

Soiling loss variability is calculated using long-term historical soiling loss estimates based on annual precipitation data for the project site and the estimated soiling profile as described in [3.4.5]. Soiling loss variability represents how much the soiling losses differs from its long-term average. When assessing soiling variability, multiple years of historical data should be taken to build a probability distribution, expressing it as a percentage of the long-term annual average soiling loss in the typical meteorological year (TMY) used in the energy estimate.

A minimum of 10 years should be used for appropriate interannual variability calculations, while 15 years is recommended. Either a normal distribution or a Kernel estimate can be used to draw a custom probability distribution around the annual data points. The probabilities should be input into the overall analysis.

3.9.5 Model uncertainty

Model uncertainty represents how far off from the long-term average all the estimates of the different FPV system losses, as well as the models that calculate these losses, could be. The model uncertainty considerations shall follow standard industry practice, and include all the energy model variables mentioned in this section of the RP.

As there are items for FPV projects which are still partially unknown and have limited supporting data, project experience and/or engineering judgement should be applied when evaluating the model uncertainty for temperature losses, soiling and mismatch.

A log-normal distribution may be assumed for each of these inputs, and the standard deviation of the distribution is determined for each input based on engineering experience. These inputs may be combined assuming an independent relationship between them.

3.9.6 Sensitivity analysis

3.9.6.1 General

There are additional sensitivity considerations which shall be considered for FPV projects, due to a general lack of long-term project data available, which contributes to an overall increased uncertainty for the long-term energy prediction of FPV systems.

By estimating the difference in energy yield for the identified variables in the sensitivity analysis a better understanding of the overall uncertainty is determined. The items described in the following subsections shall be considered in the sensitivity analysis.

3.9.6.2 Irradiance

FPV projects will be located in environments where there is a chance of the satellite irradiance data having higher uncertainty, as described in [3.2.2] and [3.9.2]. A range of sensitivities should be considered to better understand how this can have an impact on the long-term energy prediction of the project. If the project has deployed a met-station, the satellite data uncertainty for irradiance can be easily detected and mitigated.

3.9.6.3 Wave-induced mismatch losses

In some environments, the FPV system will experience mismatch losses due to waves as described in [3.7.2.2]. Since limited data is available on the effect of these mismatch losses, and since these mismatch losses will depend on the technology used by the project, (e.g. float type, multiple MPPT inverters, smart MPPT inverters, string inverters or central inverters) a range of sensitivities should be considered for this loss to better understand how this can have an impact on the long-term energy prediction of the project.

3.9.6.4 Change of azimuth due to water current

Depending on the conditions of the project locations, the FPV array, or parts of the FPV array, might move slightly away from optimal and/or intended project azimuth, due to water current and/or waves. This change can be permanent, seasonal or temporary. The degree of this movement away from optimal/intended project azimuth and the extent of this movement will be dependent on the float technology and anchoring and mooring solution used for the project. A range of sensitivities should be considered to estimate the impact this will have on the long-term energy prediction of the project.

3.9.6.5 Soiling losses

Depending on the conditions of the project locations and technology used for the project, the FPV system can experience increased soiling from bird droppings and biofouling as described in [3.4.5]. The project might also observe reduced soiling due to higher humidity, water spray and general distance to shore. Since limited data is available for soiling losses, a range of sensitivities should be considered to estimate the impact this will have on the long-term energy prediction of the project.

3.9.6.6 Thermal loss factors

Depending on the conditions of the project locations and technology used for the project, the FPV systems will observe different thermal loss factors as described in [3.5.4]. It is recommended to deploy a meteorological measurement station or use relevant project experience, relevant studies and/or engineering judgement to determine this effect. When this is not possible, a range of sensitivities to determine the effect the thermal loss factors will have on the long-term energy prediction is recommended.

3.10 Data inputs into existing energy model

If the project is operational, the measured data from the project may be inputted into an existing energy model for the project to understand if the project is under or over performing. This investigation may be further used to:

- identify arrays or inverters that are underperforming
- quantify the production loss compared with a reasonable figure expected for the design and the quality of the equipment installed
- check whether the underperformance is varying over time (seasonal patterns as an indication of other issues like shadings or temperature behaviour).

For input of operational data into an existing energy model, it is recommended to use a minimum of 12 consecutive months of available operational data. Recommended data to include in the energy model from operational data should include as a minimum:

- irradiance (GHI)
- POA irradiance
- ambient temperature
- wind speed
- wind direction
- flash test results
- soiling
- curtailment
- energy production at revenue meter
- energy production at inverter.

Measured PV module temperature for the project may be used to adjust/validate the assumptions for thermal loss factors in the initial energy model.

Based on the measured data a corrected energy prediction should be conducted.

Guidance note:

Irradiance measurements and soiling measurements (if available) carry material uncertainty even with high quality sensors. If PV module factory flash test data is not available, this can also increase the uncertainty of the assessment. Actual performance deviation of +/-3% relative to the pre-construction estimate generally demonstrates performance in line with expectation. Further improvements in the results may be possible depending on the granularity of the production data, but the known sources of uncertainty can make it difficult to distinguish measurement uncertainty from underperformance within this range without undertaking additional analysis (e.g. field investigations and or performance assessments as sub-inverter level).

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SECTION 4 GENERAL DESIGN CONSIDERATIONS

4.1 General

This section provides design principles and guidance for design of FPV systems, here defined as the floats and support structures for solar panels including the station keeping system. The following items are covered:

- design principles
- load categorization
- modelling of environmental loads
- global loads and response assessments.

4.2 Design principles

4.2.1 Safety philosophy

4.2.1.1 General

In this subsection a safety philosophy appropriate for design of FPV systems is proposed. The safety philosophy includes definition of consequence categories and target safety levels.

4.2.1.2 Consequence category methodology

It is recommended to ensure structural safety by the use of a consequence category methodology. The structure to be designed is assigned a consequence category based on the consequences of failure. The categorisation is normally determined by the purpose of the structure. For each consequence category, a target safety level can be defined in terms of an annual probability of failure.

Two consequence categories are defined:

- Consequence category 1: where failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent structure, and environmental impacts.
- Consequence category 2: where failure may well lead to unacceptable consequences of these types.

For FPV systems, which are unmanned during severe environmental loading conditions, the consequences of failure are mainly of an environmental and economic nature. A damaged system is regarded as acceptable in conjunction with consequence category 1, as long as it does not cause harm to other structures.

4.2.1.3 Target safety

The recommended target safety level for structural design of FPV systems is a nominal annual probability of failure of 10^{-4} in consequence category 1 and 10^{-5} in consequence category 2. These target safety levels are aimed at for systems whose failures are ductile and have some reserve capacity. These target safety levels apply to systems which are correctly planned and built, i.e. without systematic errors. The target safety level is the safety level aimed at for the entire system and will in practice also be the safety level for individual failure modes, since one failure mode is usually dominating. It is intended for use both in case of local failures in hot spots and in case of failures with system effects, such as failure in the weakest link of a mooring line.

4.2.2 Design aim and objective

Structures and structural elements shall be designed to:

- sustain loads liable to occur during all temporary, operating and damaged conditions as required
- ensure safe operation of the FPV system during the design life of the structure
- maintain acceptable safety for personnel and environment
- have adequate durability against deterioration during the design life of the FPV system.

The design of a structural system, its components and details shall satisfy the following requirements:

- resistance against relevant mechanical, physical and chemical deterioration shall be achieved
- fabrication and construction shall comply with relevant, recognized standards, techniques and practice
- inspection, maintenance and repair shall be possible.

Structures and structural components should possess ductile behaviour unless the specified purpose requires otherwise. Structural connections shall be designed with the aim to minimize stress concentrations and reduce complex stress flow patterns. For further details on the functional requirements of the floats making up the floating structure, see [5.3].

4.2.3 Limit states

An FPV system and its components shall be designed to a specified design life, i.e. the period of time over which the floating structure and the station-keeping system are designed to provide an acceptable minimum level of safety.

Once the design life is specified, it is recommended to apply a limit state design. A limit state is a condition beyond which a structure or structural component will no longer satisfy the design requirements. The following limit states are considered in this RP:

- Ultimate limit states (ULS) corresponding to the maximum load-carrying resistance. Examples of ULS include:
  - loss of structural resistance (excessive yielding and buckling)
  - failure of components due to brittle fracture
  - loss of static equilibrium of the structure, or part of the structure, e.g. by overturning or capsizing
  - failure of critical components of the structure caused by exceeding the ultimate resistance (which could be reduced because of repetitive loading) or the ultimate deformation of the components excessive deformations caused by ultimate loads.
- Accidental limit states (ALS) corresponding to survival conditions in a damaged condition or in the presence of abnormal environmental conditions. Examples of ALS include:
  - structural damage or failure caused by accidental loads
  - mooring line failures
  - exceedance of ultimate resistance of damaged structure
  - loss of global structural integrity after local damage or flooding.
- Fatigue limit states (FLS) corresponding to failure due to the effect of cumulative damage of cyclic loading.
- Serviceability limit states (SLS) corresponding to project-defined criteria applicable to intended use. Examples of SLS include:
  - displacements or rotations that may alter the effect of the acting forces
  - displacements or rotations that may change the distribution of loads between supported rigid objects and the supporting structure
  - excessive vibrations and accelerations producing discomfort or affecting non-structural components
  - motions that exceed the limitation of equipment
  - temperature-induced deformations
  - deformations or movements that affect the efficient use of structural or non-structural components or the operation of the structure.

The effects of corrosion/degradation which reduce the durability of the structure and affects the properties and geometrical parameters of structural and non-structural components shall be applied in all limit states:

- ULS, ALS and SLS conditions shall include the worst case maximum corrosion/degradation expected during the life of the system, as well as no corrosion/degradation if loads from this could be more onerous for any components.

- FLS condition may apply the mean corrosion/degradation for parameters such as material properties and thickness.

4.2.4 Design load cases

Analyses shall be carried out for a set of cases to ensure that the FPV system is designed to withstand all foreseen scenarios and environmental conditions. Such a set of cases are commonly denoted as design load cases.

The design load cases shall include appropriate combinations of wind, wave and current induced load effects such that these environmental combinations each have a joint annual probability of exceedance in accordance with the return period specified for the design. Water level effects shall be included, when relevant.

4.2.5 Design by partial safety factor method

4.2.5.1 General

It is recommended to use a partial safety factor method, which is based on separate assessment of the load effect in the structure due to each applied load process. In cases where it is not feasible to carry out separate assessments of the different individual process-specific load effects, design shall be done by direct simulation of the combined load effect of simultaneously applied load processes.

The partial safety factor method is a design method in which the target safety level is met, as close as possible, by applying load and resistance factors to characteristic values of the governing variables and subsequently fulfilling a specified design criterion expressed in terms of these factors and these characteristic values. The governing variables consist of:

- loads acting on the structure or load effects in the structure
- resistance of the structure or strength of the materials in the structure.

The characteristic values of loads and resistance, or of load effects and material strengths, are chosen as specific quantiles in their respective probability distributions. The requirements for the load and resistance factors should be set such that possible unfavourable realizations of loads and resistance, as well as their possible simultaneous occurrences, are accounted for to an extent which ensures that a satisfactory safety level is achieved.

Guidance note:

The load and resistance factors recommended in this RP are not yet calibrated specifically for FPV systems, by means of structural reliability methods, to match target safety level in [4.2.1.3]. The load and resistance factors are instead chosen carefully from standards used for other type of structures, e.g. floating wind, with the aim of meeting the chosen target safety level.

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4.2.5.2 The partial safety factor format

The safety level of a structure or a structural component is considered to be satisfactory when the design load effect S_d does not exceed the design resistance R_d:

$$S_d \leq R_d \tag{4.1}$$

This is the design criterion. The design criterion is also known as the design inequality. The corresponding equation $S_d = R_d$ forms the design equation.

4.2.5.3 Load effect

The load effect S can be any load effect such as an external or internal force, an internal stress in a cross section, or a deformation.

The design load effect S_d is obtained by multiplication of the characteristic load effect S_c by a specified load factor γ_s

$$S_d = S_c * \gamma_s \tag{4.2}$$

Guidance on calculation of load effects relevant for floats and anchoring and mooring are given in Table 5-1 and Table 6-2 respectively.

The characteristic value S_c of the load effect resulting from an applied load combination is defined as follows, depending on the limit state:

- ULS, the characteristic load effect whose return period is at least 50 years
- FLS, the characteristic load effect is based on the expected load effect history
- SLS and ALS, the characteristic load effect is a specified value, depending on operational requirements.

Load combinations (load cases) to arrive at the characteristic value S_c of the resulting load effect are given in Sec.5 for floats and Sec.6 for anchoring and mooring.

4.2.5.4 Resistance

The resistance, R, against a load effect, S, is the corresponding resistance such as a capacity, a yield stress or a critical deformation. The design resistance, R_d, is obtained by dividing the characteristic resistance, R_c, by a specified material factor, γ_R:

$$\mathrm{R_d} = \frac{R_c}{\gamma_R} \tag{4.3}$$

The characteristic resistance, R_c, is obtained as a specific quantile in the distribution of the resistance. It may be obtained by testing, or it may be calculated from the characteristic values of the parameters that govern the resistance. In the latter case, the functional relationship between the resistance and the governing parameters is applied.

4.2.6 Use of other recognized standards

The design principles given herein provides a framework for how to carry out structural design of floats and station-keeping systems to achieve a specified target safety level. Alternative methods are available in other applicable and recognized standards or guidelines (e.g. ISO, API, Eurocode, etc.) and may be applied. The complete methodology (design principles, load factors, environmental return periods and analysis methods) from the alternative standard or guideline shall then be applied and it shall be justified that the overall level of safety is not less than given herein.

In addition, any regional and national requirements shall be adhered to as applicable.

4.3 Categorization of loads

4.3.1 General

In this section, loads, load components and load combinations to be considered in the overall strength analysis for design of floating support structures and moorings for FPV systems are specified. Requirements for the representation of these loads and their combinations as well as their combined load effects are given. All specified relevant loads shall be taken into account in the global load estimates.

The following categorization of loads is made:

- permanent loads (G)
- variable functional loads (Q)

- environmental loads (E)
- accidental loads (A)
- deformation loads (D)
- prestressing loads (P).

The characteristic loads in the design limit states may be expressed as in Table 4-1.

Table 4-1 Basis for characteristic load in design condition

Load category	*Limit states – Operating design conditions*				
	ULS	*FLS*	*ALS*		*SLS*
			Intact structure	*Damaged structure*	
Permanent (G)	Expected value				
Variable (Q)	Specified value				
Environmental (E)	50-year return period	Expected load history	500-year return period	1-year return period	Specified value
Accidental (A)	Specified value				
Deformation (D)	Expected extreme value				
Prestressing (P)	Specified value				

Environmental loads are dominant loads in the design of FPV systems. Some of the environmental loads are site specific and others have determined characteristics. The load categories are discussed further in the subsections below.

4.3.2 Permanent loads (G)

Permanent loads are loads that will not vary in magnitude, position or direction during the period considered. These include mass of the structure and permanent ballast, mass of installed components including PV modules, cables, and other equipment, as well as pretension loads. The characteristic value of a permanent load is defined as the expected value based on accurate data of the unit, mass of the material and the volume in question.

4.3.3 Variable functional loads (Q)

Variable functional loads are loads which may vary in magnitude, position and direction during the period under consideration, and which are related to operation and normal use of the structure in question. Variable functional loads are often referred to as payload. For FPV systems, the variable functional loads include but are not limited to:

- loads on access walkways
- boat impacts from service vessels due to normal operation if access is provided via boats/vessels
- loads from workers and variable equipment on the structure.

The characteristic value of a variable functional load is the maximum or minimum specified value, whichever produces the most unfavourable load effects in the structure in question.

4.3.4 Accidental loads (A)

Accidental loads are loads related to accidental events, abnormal operations or technical failures, i.e. events that occur more rarely than the characteristic loads for design in the ULS. Accidental loads that shall be considered include but are not limited to:

- impacts from unintended collisions by vessels/debris
- loss of buoyancy
- loss of mooring line(s)
- dropped objects.

4.3.5 Deformation loads (D)

Deformation loads are loads caused by inflicted deformations such as:

- temperature loads
- creep loads
- settlements of foundations e.g. related to anchor if applicable.

4.3.6 Environmental loads (E)

4.3.6.1 General

Environmental loads are loads caused by environmental phenomena. Unless it can be demonstrated that an environmental load is insignificant or not relevant at the location, all possible environmental loads shall be assessed.

Environmental loads and load effects to be used for design shall be based on environmental data representative for the target region and relevant for the operation in question. Environmental loads and load effects to be used for design shall be determined by use of relevant methods applicable for the target region and for the operation of the structure, and taking into account the type, size and shape of the structure as well as its response characteristics.

Practical information regarding environmental conditions and environmental loads are given in Sec.2.

4.3.6.2 Environmental actions

The environmental actions, wind, wave and current, give loads whose magnitude and direction may vary with time. These shall be considered following the indications in Sec.2 for ULS, ALS and FLS, as described in Table 4-1.

A return period of 50-years is recommended for ULS. If data is not indicating otherwise, strong correlation should be assumed between wind and waves and therefore taken at the same probability level. Unless current speed is wind driven, current speed may be considered at 1/10 of the probability level of wind and waves. If reducing the current, then the 50-year current should also be assessed with the same reduction applied for wind and wave, e.g:

- 50-years wind and wave combined with 5-years current
- 50-years current combined with 5-years wind and wave.

For ALS conditions the recommended return period for the environmental actions are:

- 500-years for an intact system
- 1-year for a damaged system.

The environmental actions are stochastic in nature and will therefore give rise to stochastic loads. The expected load or load effect shall be used, i.e. the mean of max based on several seeds, unless otherwise specified in the design of a specific structural component.

Note that the extreme wind speed at a certain return period shall reflect the presence of Hurricanes, Typhon, Cyclones or other phenomena.

The appropriate boundary conditions shall be considered, e.g. the full range of water level and tide variation. For further guidance, see [4.3.6.4].

4.3.6.3 Extreme events

Loads by extreme events shall be considered, including but not limited to:

- situations of extreme water level (e.g. caused by storm surge or flood)
- earthquake
- extreme accumulation of snow and ice
- transient wind loads.

The events shall be considered one at a time in both ULS and ALS per Table 4-1. Note that for the assessment of earthquake loads, a higher return period may be required by local design codes. Unless specific safety factors are specified for these return periods, it is recommended to apply ALS safety factors provided in Table 5-1. Associated parameters for the environmental actions wind, wave and current shall be considered. If there is no correlation, e.g. between an earthquake and wind speed, only mild intensity of the environmental actions needs to be applied.

4.3.6.4 Boundary conditions

Some environmental phenomena set up boundary conditions for the FPV system in the load assessments. The value to be used depends on the type of environmental phenomena, it will either be a specified value or shall be selected conservatively as an associated value conditioned on the studied environmental parameter. Here are some examples:

- Water level and tide: specified value, advised to consider full range of variation as described in [2.9.3].
- Marine growth: specified value, the fully developed marine growth should be applied as described in [2.6.2].
- Snow and ice accumulation: if extreme waves are considered, then the distribution of snow and ice accumulation in the season of extreme waves may be considered. A range of 10 - 90% based on the cumulative distribution of snow and ice accumulation should be regarded. See [2.5] for more details.

4.3.7 Prestressing loads (P)

Prestressing loads are loads that are applied to different components, first, to induce desirable strains and stresses in the structure and second, to counterbalance undesirable strains and stresses. Prestressing can be applied as pressure, tension or torque. For instance, pretension load on bolted connection and pretension on anchors lead to lower stress range and longer fatigue lifetime for the components.

4.4 Modelling of environmental loads

4.4.1 Wave loads

4.4.1.1 General

Presence of waves result in a complex load picture on floating structures. For details about modelling of wave loads, see DNVGL-RP-C205 Sec.6 and DNVGL-RP-C205 Sec.7. The following shall be assessed when describing the effect of wave loads:

- Physical description of the wave environment. See [2.3] for guidance on how to describe surface elevation and fluid particle kinematics for either regular or irregular waves.
- Wave load model to transfer fluid pressure and wave kinematics to loads on the structure.

Some key points regarding modelling of wave loads relevant for FPV systems are provided in this section.

4.4.1.2 Hydrodynamic excitation

The following are the main wave load contributions:

- *First order wave loads*

  Wave frequency loads caused by the dynamic pressure caused by waves. First order wave loads are proportional to the wave amplitude and follow the waves in terms of frequency characteristics.
- *Wave drift loads*

  Second order slowly varying forces caused by difference frequency effects in irregular waves. The wave drift loads are proportional to the square of the wave amplitude and have frequencies far below the typical wave frequencies.
- *Drag loads*

  Wave loads caused by viscous effect from the relative velocity between the floating installation (or its members) and the water fluid particles.

In addition, a floating body moving in waves will be associated with added mass and damping due to radiating waves.

Other types of loads arise from slamming, breaking wave impact and green water due to overtopping. These effects shall be considered, if relevant, and are described in DNVGL-RP-C205.

4.4.1.3 Methods of hydrodynamic calculation

The following methods may be used to assess wave loads on floating structures:

- Morison load formula: this load model is typically used for slender structures with small diameter compared to the wave length, where the wave pattern is assumed undisturbed by the structure. May be used to model both drag and inertia loads, where the latter represents the first order wave loads.
- Boundary element method (BEM) with integration of fluid pressure over panels representing the wetted surface of the structure: used for large volume structures, where the wave pattern is influenced by the structure.
- Computational fluid dynamics (CFD): used to model the fluid motion and dynamic pressure around the structure in a more detailed manner. May be used to model viscous effects as flow separation and non-linear effects as wave impact and breaking waves.

4.4.1.4 Hydrodynamic model of floats

It is recommended to consider the hydrodynamic properties of each separate float. It is advised to use the Morison load formula, which with undisturbed wave kinematics will result in conservative load estimates. Drag and inertia coefficients shall be determined for each of the floating elements that constitutes the floating body. Coefficients may be found in DNVGL-RP-C205 App.D and DNVGL-RP-C205 App.E.

BEM can be used for refinement of the model, when wave loads become dimensioning. The first order wave loads and 2nd order mean wave loads are then expressed as frequency dependent force coefficients normalized by the wave amplitude.

Note that there will also be hydrodynamic interaction between floats. This may be studied by BEM using a multibody analysis, however these analyses are rather advanced and require sophisticated modelling. Interaction effects may also be studied in a wave tank using a scaled model of the system or by experience from existing systems.

4.4.1.5 Wave energy absorption

The effect of waves may be most important along perimeter of the FPV system. The wave energy will be absorbed when propagating through the structure, and the wave height will decay with distance from the perimeter. The reduced wave height will give reduced wave load. This can be studied by the hydrodynamic interaction between floats, preferably in a wave tank. This effect may be simplified in the model as scaled load coefficients depending on the location of the float body within the system.

4.4.1.6 Estimation of mean drift loads

The mean drift loads (2nd order wave loads) may be estimated by the Maruo's formula assuming full reflection of short waves:

$$F_{Drift} = \frac{\rho g \zeta_A^2}{2} L * \sin\theta \tag{4.4}$$

Where L is the length of the floating system subject to incoming waves of amplitude ζ_A . The angle θ is the relative angle between the perimeter, of length L, and the incoming waves.

If frequency and wave direction dependent drift coefficients, $C(\omega,\theta)$, are available from BEM-analysis, the mean drift load on one body should be calculated from the wave spectrum for irregular waves $S(\omega)$ by integration. With N bodies along the edge of the floating system subject to waves, the total load may be estimated as:

$$F_{Drift} = N * 2 \int C(\omega,\theta)\, S(\omega) d\omega \tag{4.5}$$

If there are incoming waves on multiple sides of the FPV system, the formulas may be used to estimate the mean wave drift force at each side. Note that the resulting force at each side acts normal to the perimeter, L, of the FPV system.

4.4.2 Wind loads

4.4.2.1 General

Wind leads to both static loading due to the static wind velocity and dynamic loading due to fluctuations in the wind velocity.

Wind loads are likely to be the dominant source of loading both for in-land and near shore floating PV installations. Therefore, the design wind conditions and the wind load calculations shall be carefully assessed, see Sec.2. For details about modelling of wind loads, see DNVGL-RP-C205 [5.3].

Different effect of wind loads on the installation shall be assessed, including but not limited to:

- global wind loads for dimensioning of mooring system and stress concentration between floats
- uplift of the floats
- local wind speed induced dynamic pressure.

As the wind speed varies with elevation, the height of the structure or structural component shall be considered.

4.4.2.2 Local effects

Action of wind generally results in wind pressure that act in a direction normal to the surface. When a large surface is swept by wind, frictional forces due to tangential drag shall also be considered.

For design of individual components, a time averaged wind speed may also be used, but the averaging time interval should be reduced to allow for smaller turbulence scales. For local individual panel and supporting structure checks, short duration gusts (e.g. 3s wind speed) shall be applied.

4.4.2.3 Global effects

The global wind loads will be compensated by the mooring system. The dynamic wind loads can induce low-frequency resonant horizontal plane motions of moored installations. These loads shall be modelled using a wind spectrum. Also, the spatial dependency might be important for large FPV systems, which is described by a coherence function.

For design of structures that are sensitive to dynamic excitation, the time and spatial variation of the wind speed shall be accounted for. Note that dynamic excitation can be triggered when the wind field contains energy at frequencies near the natural frequencies of the structure.

4.4.2.4 Wind force coefficients

To assess the loads, the wind force coefficients of drag and lift which describes the wind load characteristics on a floating structure shall be determined. The wind force coefficients are typically given as load per unit wind velocity and are tabulated for all directions at set intervals. For local analysis of pressure forces, also the wind pressure coefficient shall be determined.

The following methods should be used to establish wind force and pressure coefficients. The choice of method will depend on the required level of accuracy and the complexity of component shape:

- analytical formulas, see EN 1991, DNVGL-RP-C205 App.E, ASCE 7 and JIS C8955 Sec.5
- wind tunnel tests
- CFD.

Data obtained from reliable and adequate model tests in wind tunnels are recommended. If wind tunnel tests are carried out, data from the tests may be applied to validate coefficients for subsequent designs that are similar in size and shape.

4.4.2.5 Shielding

For multi-body floating structures, the shielding effects may be important. This can be modelled by scaling the wind coefficients depending on distance towards neighbouring floats. JIS C 8955 (2017) Sec.5 provides guidance on how to scale wind loads depending on float location within the FPV array. Also, DNVGL-RP-C205 [5.3.3] gives details for the shielding effect. It is advised to apply a conservative estimate based on the methods provided in these two documents, or base the shielding effect on wind tunnel tests or CFD calculations.

For an FPV system consisting of an assembly of multiple arrays the sheltering between different FPV arrays shall be assessed.

4.4.3 Current

For a site with presence of current, the effect of the current loads on the float and mooring system shall be assessed. The FPV system would typically have a large area of submerged parts potentially exposed to current forces with the main contribution from floats, however the mooring lines and power cables may also be relevant. Current would mainly give rise to static loading on the system.

To assess the loads, it is important to determine the current force coefficients which describes the current load characteristics on a floating structure. They may be obtained by the following methods depending on the required level of accuracy:

- analytical formulas, see DNVGL-RP-C205 App.F
- wind tunnel tests
- water basin/towing tank
- CFD.

Analytical formulas may be sufficient for establishing current force coefficients for simple pontoon designs.

For multi-body floating structures, also the shielding effect of current may be important. Guidance about shielding effect of current is provided in DNVGL-RP-C205 [6.10]

4.4.4 Snow and ice

If snow and ice conditions are relevant for the project site, its effect on global and local loading shall be assessed. Guidance on snow loads may be found in local codes such as EN 1991 and ASCE 7.

- Snow and ice, if present, could accumulate on the float and give increased weight.
- Sheets of ice in the water body, either intact or broken, could potentially damage the FPV system and its mooring lines.

4.4.5 Seismic effects

Seismic loads are inertial forces acting on the structure and foundation/anchor system due to ground motion. Floating structures typically act similar to base isolated structures and hence will have limited excitation due to the seismic events themselves. These loads may be negligible compared to wind and wave loads and may be ignored.

Additionally, the effect of associated sudden waves generated by seismic events may be significant and should be taken into account, especially in areas of high seismicity.

4.5 Global load and response assessment

4.5.1 General

Proper load calculations will significantly reduce the risk of failures due to overload or fatigue. The effort, in terms of complexity of load calculation model, should reflect:

- Design stage (e.g. feasibility, feed, detail design). Generally, the required effort and accuracy of load calculations would increase at later design stages.
- Location of installation. More effort should be put into the load calculations for installations located in regions exposed to large wind speeds and where it is potential for waves.
- Consequence of failure. The effort put into the load calculations should reflect the consequence of failure for the installation, the surrounding environment and other assets in proximity.

The following general principles shall be applied to a global load and response assessment:

- It shall be documented that all relevant physical effects are included.
- Justifications for any assumptions or simplifications shall be made and it shall be documented that they are accurate or conservative.

The design of floats and station-keeping systems are addressed respectively in Sec.5 and Sec.6. However, the global analysis of the integrated structure is required in both cases and addressed in this section.

This subsection introduces how the global load and response assessment ideally should be done in an advanced manner, before possible simplification using static assessment is introduced.

4.5.2 Ideal global model

4.5.2.1 General

A floating structure might constitute of large flexible single bodies or be composed of many rigid bodies in an assembly that combined forms a flexible structure on a larger scale. In a multi-body system, each rigid body is referred to as a float. There are several different float types applicable, as described more in detail in [5.2.8].

4.5.2.2 Aim and objective

The global model of an FPV system shall:

- represent the individual floating elements that constitutes the complete structure as realistically as possible
- include realistic connections between floats
- capture all relevant loads
- include the mooring system.

The model shall perform both static and dynamic load assessment with a realistic representation of the environmental actions in time domain. The global model shall be used to assess the following, including but not limited to:

- the global motions
- the mooring tension
- the forces in connection between floats
- inputs (e.g. float accelerations) for detailed structural assessments.

4.5.2.3 Motion characteristics

For the global model that constitutes of many floating elements, each element can be considered as a rigid body.

The modes of motions, also referred to as degrees of freedom (DOF), of a rigid body are:

- surge
- sway
- heave
- roll
- pitch
- yaw.

The modes of motions on a larger scale will be flexible, as there can be vertical relative motions between the rigid bodies. The global motions of the entire floating structure are mainly surge and sway. However, also heave can be considered as a global motion, e.g. for the change in water depth and for long waves relative to the length scale of the system.

Mode shapes and natural frequencies of the flexible global model may be studied by eigen-value analysis if relevant. These mode shapes could potentially be excited by waves or turbulent spatial dependent wind speed, which are effects that shall be addressed with time domain analysis.

4.5.2.4 Numerical analysis

Several software programs are available which can model a multi-body system and consider dynamic environmental loads in time domain.

In such programs, the representation of wave loads can be done either by Morison elements or frequency dependent hydrodynamic forces that are pre-calculated from a panel model applying potential flow theory (BEM). Wind and current loads can be modelled by force coefficients.

4.5.3 Static assessment

A static load assessment may be sufficient to cover critical load scenarios. It is then recommended to include dynamic effects in a simplified manner through e.g. dynamic amplification factors (DAF). For dynamic structures and at locations with more severe environmental actions, it is recommended to carry out a fully dynamic analysis to estimate the load and load-effects.

However, a static assessment by load estimation, e.g. simple scripts or spreadsheet calculations, may be useful for the following design considerations:

- local pressure loads cause by wind
- global loads to establish main float dimensions and the number of mooring lines.

These calculations are not suited to determine load distribution in a complex mooring line configuration, or stress concentration between floats. This may require an equilibrium state calculation which is better handled by a multi-body time domain analysis software.

If a static assessment is carried out based on wind loads, the following is recommended:

- obtain the mean load from a mean wind speed, e.g. using 10 min or 1 hr averaging periods
- obtain the maximum load from a gust wind speed, e.g. using 3 sec gust value.

The dynamic part of the load is obtained as the maximum load above the mean load. This approach can be combined with steady current and mean wave loads.

4.5.4 Stochastic response

4.5.4.1 Seeds and Duration

The environmental actions are stochastic in nature and will therefore give rise to stochastic load response. The long-term distribution of each parameter is derived statistically and will be associated with a certain time duration for where it is assumed to remain constant. The same duration should be applied in the load analysis to get the short-term distribution of loads within the duration.

The characteristic load effect should be calculated as a specified quantile of the extreme value distribution of short-term response. The mean of the maximum based on several seeds should be applied, unless otherwise is specified. The number of seeds that needs to be considered depend on the time scale of response, meaning the number of peaks during the considered duration of analysis. With a mooring system and presence of waves, there is a combined wave-frequency (WF) and low-frequency (LF) process which typically require a higher number of seeds to obtain reliable results.

4.5.4.2 Float motions

The motion response of a float in a stationary, short-term, environmental state shall be assessed and may conveniently be split into four components:

1) Mean displacement due to mean environmental loads.
2) Low frequency displacements, in the frequency range of the natural periods of the moored platform in surge, sway and yaw modes of motion, due to low-frequency wind loads and second-order wave loads.
3) Oscillations in the frequency range of the incoming waves, due to first-order wave loads.
4) Vortex induced motion, if relevant, e.g. if slender members are exposed to high current speeds.

4.5.4.3 Dynamic response

For dynamic structures that are sensitive to change in peak wave period (T_p) it is advised to consider a range of peak wave periods, at given H_s, to determine the governing combination. More details are provided in [2.3.4] about design conditions for waves.

4.5.4.4 Quasi-static response

For quasi-static WF response of structural elements it may be applied a regular wave, with wave height that equals the expected maximum wave height for the duration of the irregular time series.

However, this is not applicable for mooring-related responses, e.g. line tension, which are influenced by LF dynamics. For these responses the complete irregular time series shall be applied.

4.5.5 Testing and validation

4.5.5.1 General

This section provides requirements and guidance for scaled global performance testing of FPV systems. Scaled testing means that the structure is reduced (scaled) compared to the full-scale structure intended for operation. Scaled testing provides insight on system performance that is difficult to obtain from analyses. The results of scaled testing can be a means of identifying key failure modes and thereby reducing the risks associated with development and installation of novel concepts. Furthermore, it can provide a means of confirming the assumptions made in early design stages, study the global behaviour of the system and be used to calibrate a numerical model.

Scaled testing can be beneficial with respect to demonstrate performance when developing new designs or when applying a known design in more severe environmental conditions than previously exposed to.

Two types of scaled testing, model (scale) testing and pilot (scale) testing are described in the following sub-sections.

4.5.5.2 Model testing

Small scale hydrodynamic model testing is a method that is well-established within marine engineering. Testing is typically carried out in wave tanks. The results may be used to:

- establish hydrodynamic load characteristics
- global system concept and design verification
- validation/calibration of numerical models
- estimation of extreme loads and response.

The testing is carried out in a controlled environment with capabilities to realistically represent waves, and often wind and current.

The most common way of scaling models is by use of Froude’s scaling law. The model scale varies significantly, usually from 1:10 to 1:100, depending on the capabilities of the wave tank and size and shape of the full-scale structure. As FPV systems are large in size and often have a high number of mooring lines, it would in most cases be necessary to simplify the model. For very small-scale models it is challenging to correctly scale the individual floats.. For such cases, it is rather advised to reduce the number of floats in the model compared to the full-scale structure. Furthermore, simplifications to the mooring model can be made by lumping several mooring lines together as one equivalent line.

It would normally not be required to carry out hydrodynamic model tests for a standard FPV system. However, it is recommended to do so for novel designs and for structures that will be exposed to large environmental forces. Furthermore, results from hydrodynamic model tests may be utilised later for designs/projects that are similar in shape and characteristics as the design that has been tested.

More details, recommendations and guidance on hydrodynamic model testing are found in DNVGL-RP-C205 Sec.10.

4.5.5.3 Pilot testing

Pilot testing provides a useful means of testing the performance of the design in a real operating water environment. For novel designs with limited operational experience, pilot testing is recommended before proceeding to full-scale installation, as this can contribute to decrease risks and achieve concept bankability.

Pilot testing may be carried out for a reduced number of floats. The dimensions of the floats, the connection between individual floats and the mooring system should be as close to the full-scale design as possible for maximum benefit of performance assessment. Multiple objectives can simultaneously be achieved through pilot testing, such as verification of design assumptions, assessment of floats and mooring system performance and yield assessment.

Key parameters should ideally be measured in the pilot test. This includes the environmental actions, mooring forces, forces between floats and forces applied to solar panels at different locations in the pilot. Reliable and accurate measurement of these parameters can be used to verify numerical models and design assumptions.

SECTION 5 FLOATS

5.1 General

This section details the composition of floats within a floating structure and provides requirements for functioning of the floats. Recommendations are provided on design and testing requirements applicable to materials and sub-assembly of floats.

5.2 System definition

5.2.1 General

The objectives of this subsection are to define floats in a floating structure, define configurations within an FPV array and identify materials which may be used for floats.

The floats in a floating structure are key structures ensuring power generating equipment are kept afloat and providing access to the power generating equipment. The equipment which may be located on floats include:

- PV modules
- inverters
- transformers
- cables
- combiner boxes (other cabinets, e.g. monitoring cabinets)
- mounting structures.

An FPV array will also include floats for walkways and may include floats for mooring. Individual floats or collection of floats may support multiple equipment or functions. See [5.3] for functional requirements of floats.

Floats for the key equipment are defined in the following subsections.

5.2.2 Floats for PV modules

Floats for PV modules are used to mount PV modules and keep the PV equipment afloat. The floats shall function as defined in [5.3.2] and comply with the performance criteria as defined in [5.5.2].

Guidance note:

The floats for PV modules may vary in their footprint depending on the angle of inclination selected, configuration of PV modules (i.e. east-west configuration vs single side facing and 60 vs 72 cell PV module) and the maximum loads expected, see [4.3] for details on load cases.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

The floats for PV technology may also function as walkways and support cables or combiner boxes.

5.2.3 Floats for inverters or combiner boxes

Floats for inverters are used to mount inverter technology and keep the equipment afloat. These floats shall function as defined in [5.3.3] and comply with the performance criteria as defined in [5.5.3].

The inverters may at times be located on land close to the FPV system, depending on specific design considerations. If the functional requirements and performance criteria for the floats supporting inverters cannot be fulfilled, see[5.3.3] and [5.5.3], then the inverters shall be installed on land.

The floats for inverter may also function as walkways and support cables or combiner boxes.

5.2.4 Floats for transformers

Floats for transformers are used to mount transformer and supporting switching equipment and keep the equipment afloat. These floats shall function as defined in [5.3.4] and comply with the performance criteria as defined in [5.5.4].

The transformers may at times be located on land close to the FPV system, depending on specific design considerations. If the functional requirements and performance criteria for the floats supporting transformers are not fulfilled, see [5.3.4] and [5.5.4], then the transformers shall be installed on land.

Cables and connectors which are not to be supported and protected by floats and are expected to be in contact with the water body shall be of suitable marine grade and designed for submerged usage. See [8.4.3] for more details.

The floats for transformers may also function as walkways and support cables or inverters.

5.2.5 Floats for cables

Floats for cables are used to provide passage and support for cables connecting the PV technology and keep the cables away from water body. The floats may be used for DC and AC cables connecting to inverter and transformer equipment. These floats shall function as defined in [5.3.5] and comply with the performance criteria as defined in [5.5.5].

The floats for cables may also function as walkways.

5.2.6 Floats for walkways

Floats for walkways are used to provide access to key equipment installed on an FPV array. These floats are required for maintenance activities. These floats shall function as defined in [5.3.6] and comply with the performance criteria as defined in [5.5.6].

5.2.7 Floats for mounting structure

Floats for mounting structure are used to mount structural frameworks. The structural frameworks may create the platform for the following equipment:

- PV technology
- inverters
- combiner boxes
- cables
- transformers.

The floats shall keep the structural frameworks and all equipment attached to the frameworks afloat. These floats shall function as defined in [5.3.7] and comply with the performance criteria as defined in [5.5.7].

Guidance note:

If the mounting structure float incorporates additional equipment, then the float should add the functional requirements and performance criteria for the respective float's category (e.g. if the mounting structure float also adds support for walkways the functional requirements should include those in [5.3.6]. and the performance criteria should include those in [5.5.6])

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

The floats supporting mounting structure may also function as walkways.

5.2.8 Types of FPV arrays

5.2.8.1 Structures

The most common FPV arrays are structurally defined into three main categories. These are:

1) Pure floats (or floats with PV modules), see Figure 5-1.
2) Modular rafts, see Figure 5-2.
3) Membranes, see Figure 5-3.

Other technologies with structurally different FPV array may be available but these are not addressed specifically in this document. This document may be updated to address future emerging FPV array structures.

The configurations within these structural categories are discussed below, see [5.2.8.2].

Pure floats

This category of FPV array is characterised by direct mounting of PV modules onto the floats. The means for fastening PV generating equipment (e.g. clamps/fixings) are incorporated into the floating structure. The pure floats FPV array may be designed to carry multiple PV modules per float.

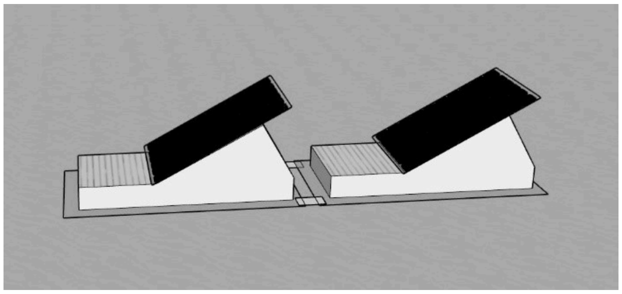

Figure 5-1 Schematic of pure floats

Modular rafts

This category of FPV array is typified by structural frameworks supported by floats. The means of fastening PV generating equipment (e.g. clamps/fixings) are attached to the structural frameworks. The structural frameworks may carry several PV modules and also support combiner boxes, inverters and/or transformers.

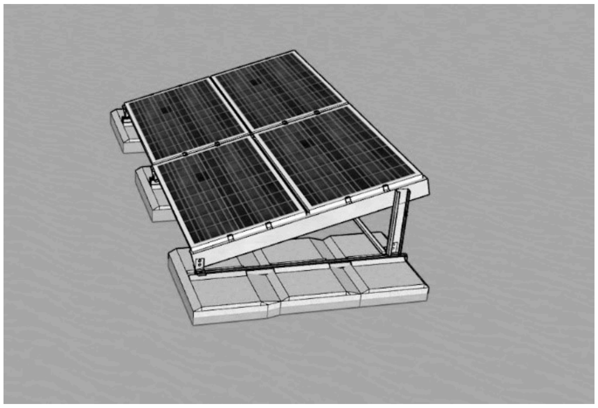

Figure 5-2 Schematic of modular rafts

Membranes

This category of FPV array is typified by PV generating technology attached to some form of reinforced membrane which is supported by additional structures, such as tubular rings to provide buoyancy support. The amalgamation of the reinforced membrane and tubular ring is the float and the floating structure in such an FPV array. The tubular ring may also support combiner boxes.

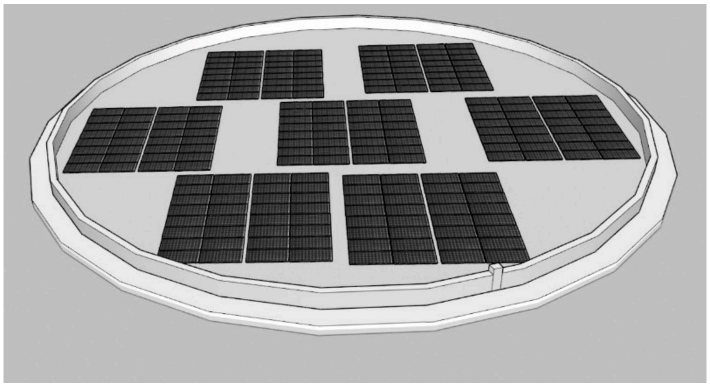

Figure 5-3 Schematic of membrane floats

5.2.8.2 Configurations

The FPV arrays may be arranged into various configurations depending on system design, the environment and FPV project requirements. The pure float and modular raft FPV array types may be designed to have single azimuth / single inclination or dual azimuth / single inclination solar PV system. These FPV arrays could be designed to have horizontal or vertical axis tracking.

The membrane FPV array type is limited to horizontal solar PV system design.

The functional requirements, see [5.3], and performance criteria, see [5.5], of all the floats type applicable to and present in a specific FPV system shall be fulfilled for the chosen FPV array and configuration type. Specific FPV arrays may include only part of the identified floats type identified in [5.2].

An FPV array may be either single body (i.e. single floating structure without internal interconnections to multiple floats) or multi body (i.e. multiple floating structures with internal interconnections between them).

5.2.8.3 Materials

Material specifications shall be established for all structural materials utilised in floats. Such materials shall be suitable for their intended purpose and have adequate properties in all relevant design conditions.

When considering criteria appropriate to material grade selection, adequate consideration should be given to all relevant phases in the life cycle of the unit. In this context there may be conditions and criteria, other than those from the in-service, operational phase, which may govern the design requirements with respect to the selection of materials. Such criteria may, for example, consist of design temperature and stress levels during operation. For the design considerations of floats, see [5.4].

The materials typically used for floats are discussed in sub sections below. Single materials or combination of materials may be used for floats. The materials to be used for fabrication of floats must fulfil the material requirements, see [5.6].

Synthetic polymer (heavy duty plastics)

Synthetic polymers (heavy duty plastics) have regularly been used in floats. Heavy duty plastics offer floating solution that is lightweight and easy to assemble (particularly in modular designs).

Some examples of heavy-duty plastics used in floats include:

- HDPE (high density polyethylene)
- PE (polyethylene).

Metals

Metals have regularly been used in floats. Metals offer more rigid floating solutions (particularly in modular raft FPV array design)

Some examples of metals used in floats include:

- aluminium

- stainless steel
- carbon steel (with corrosion resistant coating).

Others

Use of other materials may be considered providing that the material requirements are fulfilled as per [5.6] and the finished float shall fulfil its functional requirements and performance criteria as per [5.3] and [5.5] respectively.

Some materials which have been used either in prototyping or testing include:

- PU (polyurethane foam)
- fibreglass with epoxy or polyester resin
- ferrocement.

5.2.9 Float connections

The type of connections that exist in a floating structure are dependent on the type of FPV array and their position in the floating structure.

The internal interconnections between floats are used to link multiple floats with various functions within a floating structure. These interconnections shall function as defined in [5.3.9] and comply with the performance criteria as defined in [5.5.9].

> **Guidance note:**
>
> The float-to-PV module connection may vary in form depending on the form factor of the float supporting PV technology and the system design (PV module inclination).
>
> ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

5.3 Functional requirements

5.3.1 General

This section provides requirements on how the floats that form an FPV array shall function. The functional requirements for the following floats are detailed in the following subsections:

- floats supporting PV modules
- floats supporting inverters/combiner boxes
- floats supporting transformers
- floats supporting cable trays/cabling
- floats connecting to walkways
- floats supporting mounting structure
- floats supporting mooring system
- floats interconnections.

FPV array may be designed such that a float serves multiple functions, e.g. floats supporting PV modules may also support walkways and floats supporting transformers may also supports cabling.

A float which serves multiple functions shall fulfil the functional requirements under all respective functions.

5.3.2 Floats supporting PV modules

The floats supporting PV modules shall fulfil the following functional requirements:

1) The float shall stay afloat and maintain its structural integrity for its designed lifetime.
   a) Float shall be stable and provide adequate buoyancy.
   b) Float shall be durable and maintain structural integrity for given location over its lifetime.
   c) Float shall withstand hydrodynamic and wind loads expected during its lifetime (location specific).
2) The float shall be able to retain the PV modules as designed.
   a) Float shall have adequate strength to withstand and transfer all forces.
   b) Float shall ensure that the PV modules remain fixed under loads.
   c) Float shall ensure that the transfer of forces to the modules does not exceed the design capacity of the PV modules.
   d) Float shall keep the intended orientation (for non-tracking system).
3) The float shall allow for unrestricted maintenance activities.
   a) Junction boxes and string connectors shall be accessible.
   b) Parts (including PV module, floats, clamps) shall be easily removable once FPV system has been deployed.
4) The float should allow, as much as possible depending on the design, air to circulate between the float and the PV modules.
5) The float shall minimise stresses on all cables.

5.3.3 Floats supporting inverters/combiner boxes

The floats supporting inverter/combiner boxes shall fulfil the following functional requirements:

1) The float shall stay afloat for its designed lifetime.
   a) Float shall be stable and provide adequate buoyancy.
   b) Float shall be durable and maintain structural integrity for the given location over its lifetime.
   c) Float shall withstand hydrodynamic and wind loads expected during its lifetime (location specific).
2) The float shall be able to retain the equipment as designed.
   a) The float shall have adequate strength to withstand and transfer all forces.
3) The float shall allow for unrestricted maintenance activities.
   a) All equipment on the float shall be accessible.
   b) Cabinets/cable terminations shall be accessible.
   c) The float shall allow for replacement of components without impacting functioning of surrounding floats.
4) The float shall minimise stresses on all cables (including DC and AC cables).

5.3.4 Floats supporting transformers

The floats supporting transformers shall fulfil the following functional requirements:

1) The float shall stay afloat for its designed lifetime.
   a) Float shall be stable and provide adequate buoyancy.
   b) Float shall be durable and maintain structural integrity for given location over its lifetime.
   c) Float shall withstand all loads (including hydrodynamic and wind loads) expected during its lifetime (location specific).
   d) Float shall withstand thermal loads from the transformer in the operational condition.
2) The float shall be able to retain the equipment as designed.
   a) The platform on the float shall have adequate strength to withstand and transfer all forces.

3) The float shall provide stable platform for the transformer and its station (if applicable).
    a) The platform on the float shall be stable and levelled under all loads.
    b) The platform on the float shall be adequate for all expected maintenance activities.
4) The float shall allow for unrestricted maintenance activities.
    a) The float shall be accessible without interfering with other floats.
    b) The float shall provide adequate docking provisions.
    c) The float shall provide access to cable terminations from the platform.
5) The float shall minimise stresses on all cables (including MV and HV AC cables).

5.3.5 Floats supporting cable trays/cabling

The floats supporting cabling shall fulfil the following functional requirements:

1) The float shall stay afloat and maintain structural integrity for its designed lifetime.
    a) Float shall be stable and provide adequate buoyancy.
    b) Float shall be durable and maintain structural integrity for the given location over its lifetime.
    c) Float shall withstand hydrodynamic and wind loads expected during its lifetime (location specific).
2) The float shall be able to retain the equipment (all cables) as designed.
    a) The float shall have adequate strength to withstand and transfer all forces.
3) The float shall provide appropriate structure for secure cabling solution.
    a) The structure on the float shall ensure that the cable has limited movement (slack).
    b) The structure on the float shall ensure adequate protection from mechanical wear.
    c) The structure on the float shall ensure adequate protection from environmental wear (UV exposure and water).
4) The structure on the float shall ensure unrestricted access for maintenance activities.
    a) All cabling shall be accessible.
    b) The float shall allow for replacement of cabling without impacting functioning of surrounding floats.
5) The float shall minimise stresses on all cables (including MV and HV AC cables).

5.3.6 Floats supporting walkways

The floats supporting walkways shall fulfil the following functional requirements:

1) The float shall stay afloat and maintain structural integrity for its designed lifetime.
    a) Float shall be stable and provide adequate buoyancy.
    b) Float shall be durable and maintain structural integrity for given location over its lifetime.
    c) Float shall withstand hydrodynamic and wind loads expected during its lifetime (location specific).
2) The float shall provide adequate platform for maintenance activities.
    a) The platform shall be stable for expected maintenance load, including, but not limited to, weight of personnel and weight of equipment being carried on the walkways.
    b) The platform shall provide sufficient space to carry out expected maintenance works.
    c) The platform shall provide adequate docking provisions.
    d) The float shall allow for replacement of components without impacting functioning of surrounding floats.
    e) The float shall provide safe platform for maintenance personnel.

3) The float shall allow for unrestricted access to other adjoining floats.
    a) The walkways shall have adequate width for unrestricted access.
    b) The walkway shall maintain a continuous path.
4) The float shall provide suitable access for emergency situations.

5.3.7 Floats supporting mounting structure

The floats supporting mounting structures shall fulfil the following functional requirements:

1) The float shall stay afloat and maintain structural integrity for its designed lifetime.
    a) Float shall be stable and provide adequate buoyancy.
    b) Float shall be durable and maintain structural integrity for given location over its lifetime.
    c) Float shall withstand hydrodynamic and wind loads expected during its lifetime (location specific).
2) The float shall keep the equipment as designed.
    a) The float shall have adequate strength to withstand and transfer all forces.
    b) Float shall ensure that the PV modules and frameworks remain fixed under expected loads.
3) The float shall allow for unrestricted maintenance activities.
    a) All equipment and connections/joints within of the mounting structure shall be accessible.
    b) The float shall allow for replacement of components without impacting functioning of surrounding floats.

5.3.8 Floats connecting to mooring system

The floats supporting mooring connection shall fulfil the following functional requirements:

1) The float shall stay afloat and maintain structural integrity for its designed lifetime.
    a) Float shall be stable and provide adequate buoyancy.
    b) Float shall be durable for given location.
    c) Float shall withstand hydrodynamic and wind loads expected during its lifetime (location specific).
2) The float shall be able to withstand all forces expected during its designed life and distribute forces as expected.
    a) The float shall be able to distribute forces from the mooring line into the floating structure.
    b) Should provide sufficient local buoyancy to withstand the vertical mooring forces.
3) The float shall allow for unrestricted access for to connection points to the mooring system for maintenance activities.

5.3.9 Float interconnections

The interconnection between floats shall fulfil the following functional requirements:

1) The interconnection shall be able to keep multiple floats connected as designed for the lifetime of the floats.
    a) The interconnection shall be able to withstand all expected forces during project lifetime without failure.
    b) The interconnection shall be durable for the given location and use, i.e. moving joints shall have sufficient wear resistance to accommodative the movement for the design life of the joint.
    c) The interconnection shall limit the movement as per the specification of the floats to mitigate potential impact from neighbouring floats.

2) The interconnection shall have unrestricted access for maintenance activities.

    a) The components that make up the interconnection shall be easily accessible and shall be replaceable following installation.

5.4 Design considerations

5.4.1 General

This section introduces the design load cases and the load and material factors. The load cases are based on the global loads explained in [4.3]. Design considerations specify the load cases during operational, maintenance and special conditions.

In general, a site-specific load analysis based on the design consideration shall be performed, see Sec.2.

Conventional PV systems on land and buildings are usually engineered and assessed assuming static loads: dead weight, snow and wind loads. FPV arrays are subjected to dynamic loads due to waves, currents and the mooring system.

Safety philosophy of structural design is discussed in [4.2].

5.4.2 Partial safety factor method

5.4.2.1 General

The partial safety factor method is detailed in [4.2.5], the targeted safety level is achieved as closely as possible by applying resistance and load factors on the characteristic values of governing variables to meet the design criteria.

As an alternative or as a supplement to analytical methods, determination of load effects or resistance may in some cases be based either on testing or on observation of structural performance of models or full-scale structures.

Structural reliability analysis methods for direct probability-based design may also be applicable to special case design problems, to calibrate the load and resistance factors to be used in the partial safety factor method, and to design for conditions where limited experience exists.

5.4.2.2 Material factor

The material factors account for:

- unfavourable deviation in the material resistance from characteristic values
- possible reduction of the material resistance in the structure.

Guidance on material factors for ULS and FLS of metallic material and composite material may be found in different international and local standards. Material factors may be obtained from physical testing of materials. For further guidance, see EN1990-2002 Annex A1, DNVGL-OS-C101 Ch.2 for steel material, and DNVGL-ST-C501 App.E for composite material. Material factors for aluminium may be obtained from EN 1999-1-1.

Guidance note:

Material factors for polymer may be obtained from empirical tensile strength data.

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Design against the FLS is based on an overall design fatigue factor (DFF) applied to a characteristic cumulative damage, with unfactored loads and material factor of 1.0.

The limit states are discussed further in [5.4.3]. For ALS and SLS limit state, the material factor should be taken as 1.0.

5.4.2.3 Load factors

Load factors accounts for:

- possible unfavourable deviation of the loads from characteristic values
- the reduced probability that various loads acting together will act simultaneously at the characteristic value
- uncertainties in the model and analysis used for determination of load effects, see [4.2.1.2] for FPV systems consequence category.

Table 5-1 below provides five sets of safety factors for load categories form a load combination for the ULS and ALS design load cases which has been inspired from DNVGL-ST-0119 Table 5-1. See [4.3] for categorization of loads.

Table 5-1 Load factor γ_f for ULS and ALS

Load factor set	*Limit state*	*Load categories*					
		G	*Q*	*E – with consequence category of*		*D*	*P*
				1	*2*		
(a)	ULS	1.25	1.25	0.7^1		1.0	$0.9/1.1^3$
(b)	ULS	1.0^2	1.0	1.35	1.55	1.0	$0.9/1.1^3$
(d)	ALS for intact structure	1.0^2	1.0	1.0	1.15	1.0	$0.9/1.1^3$
I	ALS for damaged structure	1.0^2	1.0	1.0	1.15	1.0	$0.9/1.1^3$

Load categories are:

G = permanent load.

Q = variable functional load, normally relevant only for design against boat impacts and for local design of platforms.

E = environmental load.

D = deformation load.

P = prestressing load.

For description of load categories, see [4.3] and Sec.2.

1) When environmental loads shall be combined with functional loads from boat impacts, the environmental load factor should be increased from 0.7 to 1.0 to reflect that boat impacts are correlated with the wave conditions.

2) It is assumed that tight weight control of the structure is performed for floats. If sensitivity studies show risk for excessive dynamic excitations, the load factors for permanent loads should be varied between 0.9 and 1.1.

3) The most conservative value of 0.9 and 1.1 should be used as load factor the design.

For analysis of the ULS, the sets denoted '(a)' and '(b)' in Table 5-1 should be used when the characteristic environmental load or load effect is established as the 98% quantile in the distribution of the annual maximum load or load effect (50 year return period).

Load factor set '(a)' is governing when the variable functional loads like design against pretension, lifting forces and hydrostatic pressures is governing. Also, load factor set '(a)' is of relevance for design of secondary structures such as boat landings, fenders and lay down areas, for which variable functional loads from boat impacts are the dominating loads.

Load factor set '(b)' is used for ULS design when the environmental load is the dominating load, for instance, the high-speed wind during FPV array operation.

For analysis of the ALS, the load factor set denoted '(d)' should be used for the accident analysis and the load factor set denoted 'I' should be used for post-accident situation. For further explanation of ALS, see [5.4.3.3].

The load factor, γ_f, in the FLS should be 1.0 for all load categories (limited to metallic components).

5.4.3 Limit states of design

5.4.3.1 General

Limit states are discussed in [4.2.3]. Also, it is explained how to determine the global loading on the floats, see Sec.3.

Loads and load combinations considered shall be selected to assess effects of the most onerous design actions on each component being designed, which may vary from component to component.

Guidance note 1:

The design wind pressure to be considered for design of panel, panels to float connection clamp and for individual floats will be different from the wind pressure to be considered for design of mooring lines, spreader bars and float interconnections due to reduced correlation between forces and averaging out of forces over a large area.

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Wave and current phenomena are generally prevalent in water bodies with large area and high depths. Additionally, in inland reservoirs, waves are generally induced by wind action. For estimation of wave data for design, see [2.3.5].

Verification of the structural members and joints including tubular, non-tubular members, shell with and without stiffeners and bolted connections shall be done according to local and international design codes.

Guidance note 2:

The structural checks may be performed using local and international standards. See Eurocode 1993-1-3 and Norsok N-004 for tubular members and joints checks. See DNVGL-ST-0126 and Eurocode 1993-1-6 for the design of shell structures. See Eurocode 1993-1-1 for the capacity and buckling checks of profiles. See Eurocode 1993-1-8 for design of slip resistance bolt connections and end-plate bolt connections.

Durability tests such as ASTM D2990 – 17 may be used for the design of polymer floats.

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5.4.3.2 Ultimate limit states

This section gives recommendations and requirement for checking of ultimate limit states for typical structural elements used in floats and floating structure.

The ultimate strength capacity of structural elements shall be assessed using a rational, justifiable, engineering approach. Structural capacity checks of all structural components shall be performed. The capacity checks could consider both excessive yielding and buckling under all environmental loads, see [4.3.6] for environmental loads act on floats and floating structure.

Ultimate limit states analysis shall cover all extreme load scenarios include the lifting and installation loads, flooding due to rainfall (depending on design), wave overtopping and stranding load cases.

Wind, wave and snow are the dominant environmental loads on the FPV array. These loads shall be taken into account in the ULS load combinations.

Submerging of the FPV array may be allowed under ULS condition only if the electrical equipment is designed to be submerged, see Sec.8.

The structural analysis may be carried out as linear elastic, simplified rigid-plastic, or elastic-plastic analyses. In all cases, the structural detailing with respect to strength and ductility requirement shall conform to the assumptions made for the analysis. When plastic or elastic-plastic analyses are used for structures exposed to cyclic loading, e.g. wave loads, checks shall be carried out to verify that the structure will shake down without excessive plastic deformations or fracture due to repeated yielding. A characteristic or design cyclic load history needs to be defined in such a way that the structural reliability in case of cyclic loading, e.g. storm loading, is not less than the structural reliability for ULS for non-cyclic loads. If plastic or elastic-plastic structural analyses are used for determining the sectional stress resultants, limitations to the width thickness ratios apply. Relevant width thickness ratios are found in the relevant codes used for capacity checks.

5.4.3.3 Accidental limit states

ALS shall in principle be assessed for all components. Safety assessment may be carried out according to DNVGL-OS-A101 App.A.

The floats and floating structures shall be checked in two steps:

a) Resistance of the structure against the accidental loads.
b) Post-accident resistance of the components against the environmental loads only if the structure is damaged by the accident.

Guidance note 1:

See DNVGL-RP-C204 for further guidance on the design of the structures exposed to the accidental loads.

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Accidental loads are loads related to accidental events, abnormal operations or technical failure, i.e. events that occur more rarely than the characteristic loads for design in the ULS. Accidental loads that may be considered include:

- impacts from unintended collisions by drifting service vessels/debris
- impact from dropped objects
- failure of a mooring line/anchor.

The design of the FPV array against accidental loads may be done by direct calculation of the effects imposed by the loads on the structure, or indirectly, by design of the structure as tolerable to accidents. Examples of the latter are design of floats which provides sufficient integrity to survive certain piercing and impact scenarios without further calculations.

Guidance note 2:

Floats and floating structures often experience the impact scenarios from debris flows.

Depending on site specific risk assessment, fire and explosions may be avoided and may be ignored in the ALS.

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5.4.3.4 Serviceability limit states

Serviceability limit states for floats and floating structures are associated with:

- deflections/stresses which may prevent the intended operation of equipment
- stresses, deflection and vibrations which may cause hinderance during maintenance.

Serviceability limit state loads could be caused by normal environmental conditions and maintenance operations.

Maintenance operations shall be foreseen in the design phase and the loads and deflections on the sidewalks, couplings between the float compartments shall be checked.

5.4.3.5 Fatigue limit states

Components made of metal and polymer that are exposed to cyclic loading may weaken due to fatigue. Progressive and localized structural damage and growth of cracks may occur during lifetime of the FPV system.

To ensure that the float structure will fulfil its intended function, a fatigue assessment shall be carried out for each individual component which is subject to fatigue loading. Wherever appropriate, the fatigue assessment should be supported by a detailed fatigue analysis.

The resistance against fatigue is normally given as S-N curves, i.e. stress range (S) versus number of cycles to failure (N) based on fatigue tests. Fatigue failure should be defined as when the crack has grown through the thickness of the material. To verify the float structure and components, all environmental load with cyclic behaviour shall be taken into account.

Guidance note:

A fatigue assessment comprises a fatigue analysis as well as a capacity check of structural members. See DNVGL-RP-C203 for further information on the fatigue assessment of steel components in the floating structure.

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The design fatigue life for structural components shall be based on the specified service life of the structure.

Design fatigue factors (DFF) shall be applied to reduce the probability for fatigue failures. The DFFs are dependent on the significance of the structural components with respect to structural integrity and availability for inspection and repair.

DFFs shall be applied to the design fatigue life. The calculated fatigue life shall be longer than the design fatigue life multiplied by the DFF.

The design requirement may alternatively be expressed as the cumulative damage ratio for the number of load cycles of the defined design fatigue life multiplied with the DFF shall be less or equal to 1.0.

The design fatigue factors in Table 5-2 are valid for units with low consequence of failure and where it is demonstrated that the structure satisfies the requirement to damaged condition according to the ALS with failure in the actual element as the defined damage.

Table 5-2 The DFF value for different metallic structural element

Structural element	*DFF*
Internal structure, accessible and not welded directly to the submerged part	1
External structure, accessible for regular inspection and repair in dry and clean conditions, e.g., welds and bolted connection in PV mounting structure of modular rafts	1
Internal structure, accessible and welded directly to the submerged part, e.g. any attachments to the floats	2
External structure not accessible for inspection and repair in dry and clean conditions e.g. anchors connection	2
Non-accessible areas, areas not planned to be accessible for inspection and repair during operation	3

DFF for polymer material of a give float may be obtained either by material testing or provided by the manufacturer.

The DFF for polymer material may be derived through tests according to [5.7.2] using 80% material strength and 100,000 number of cycles. DFF for other materials such as ferrocement/aluminium should be assessed on a case by case basis.

5.4.3.6 Other specific limit states

Unless noted otherwise, a specific design check should be performed for stranded condition (i.e zero water level) if the ground basin slope is >5% (i.e. irregular basin) or is considered to be rocky.

Guidance note 1:

Additional intermediate water levels, leading to partial stranding, may also be explored if deemed necessary, depending on the site conditions.

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The effect of associated sudden waves generated by seismic events may be significant and should be taken into account, especially in areas of high seismicity.

Guidance note 2:

FPV system typically act similar to base isolated structures and hence will have limited excitation due to the seismic events themselves. Hence the seismic loads may be negligible compared to wind and wave loads and may be ignored, unless pretension in mooring lines are employed.

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5.5 Performance criteria

5.5.1 General

This subsection details the minimum performance level required in relation to the functional requirements of the floats in a floating structure. A summary of the key functional requirements (both 1st level and 2nd level) for the floats can be found in Table 5-3. For complete functional requirements, see [5.3].

Table 5-3 Functional Requirements for floats

Float functional requirements	*PV module floats*	*Inverters/ combiner boxes floats*	*Transformer floats*	*Cabling floats*	*Walkway floats*	*Mounting structure floats*	*Mooring system floats*	*Float inter connections*
Staying afloat and maintaining its structural integrity	✓	✓	✓	✓	✓	✓	✓	
Retaining the equipment as designed	✓	✓	✓	✓		✓		
Allow for unrestricted maintenance activities	✓	✓	✓	✓	✓	✓	✓	✓
Provide stable platform for transformer			✓					
Minimise stresses on all cables	✓	✓	✓	✓				
Provide adequate platform for maintenance activities			✓		✓			
Unrestricted access to other adjoining floats					✓			
Withstand and distribute all expected forces during its design life	✓	✓	✓	✓	✓	✓	✓	✓
Provide secure cabling solution				✓				
Keep multiple floats connected as designed for their lifetime								✓

The performance criteria will be defined for the following elements in the following subsections:

- floats supporting PV modules
- floats supporting transformers
- floats supporting inverters/combiner boxes
- floats supporting walkways
- floats connecting to mooring system
- floats supporting mounting structure
- floats supporting cable trays/cabling
- floats interconnections.

The following performance criteria are common to all floats in an FPV system:

- All floats shall have sufficient total available buoyancy and distribution of buoyancy to ensure stability of the floating structure under all service conditions and expected loads. The expected loads and their assessment are discussed in [4.3].

  Guidance note 1:

  The stability requirements for floats are based on righting moment curves with acceptance criteria expressed in terms of requirements for the area of the righting moment curve relative to the area of the wind heeling moment curve and, in special cases, in terms of a simple requirement for the location of the metacentric height, GM. Damage stability requirements of FPV arrays using concepts similar to barges, semi-submersibles, spars or TLPs may use the requirements given in DNVGL-ST-0119 Sec.10. As an alternative, the stability may be assessed by establishing the restoring forces against pitch and roll from water plane area, buoyancy, and station keeping system (only for evaluation of intact stability, not for evaluation of damaged stability) and may be accepted as sufficient provided adequate acceptance criteria in terms of energy requirements for the restoring forces can be established and met. Restoring forces may be calculated in accordance with specifications given in DNVGL-RP-C205 Sec.7.

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- All floats shall be able to withstand maximum design loads and fulfil their respective functional requirements, see [5.3], at the end of their design life.
- The floats shall not fail under maximum forces to be exerted on the respective floats,
- The floats shall have adequate stiffness to transfer maximum forces (i.e. the force that reaches the ULS of the structure, see [5.4] for more information on ULS) to be exerted without excessive permanent deformation which impairs the function of the float or FPV array.
- The floats which are supporting equipment shall ensure that the equipment is not subjected to deformation or loads outside of their allowable ranges.
- The floats should be suitable to be stranded to the bed of the water body, if site conditions assessment highlights possibility of this scenario, taking into consideration site specific bed conditions.

  Guidance note 2:

  This criterion is dependent on the likelihood of low water level in the water body. Site bed may include rocks and other obstacles creating point loads. This may be considered in the design.

  ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

- Multiple floats shall not share single rigid equipment (i.e. PV modules, inverters, combiner boxes or transformers) without specific reinforcement to prevent float relative movement.

5.5.2 Performance criteria for floats supporting PV modules

The float shall have long-term tensile strength to withstand all loads applied to them for the duration of their design life. Loads and numerical assessment to assess load cases are detailed in [4.3] and [4.4].

The fixings for PV modules shall be tested to withstand expected forces and ensure that forces applied to the PV modules do not exceed the PV module design capacity. The forces shall transfer from the PV module fixings to the floats and the PV modules shall not come under high stresses.

The structural design of the floats shall not rely on the strength of the PV module (i.e. PV modules shall not be used as structural elements to stiffen the float design).

Guidance note 1:

The PV modules may undergo electroluminescence testing before and after pilot testing, see [4.5.5.3], to ensure that the float for PV modules has successfully kept out forces from the PV modules.

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To ensure unrestricted maintenance activities on the float the performance, criteria are as follows:

1) The junction boxes and string connectors shall be easily reachable.
2) Exchange of parts shall be carried out with tools readily available to maintenance personnel.

The float should have sufficient space between the PV modules and the float, depending on the design, to allow for air to circulate and the floats shall ensure that the DC solar cables are not bent beyond their design limits.

Guidance note 2:

For types of floating structures in which the PV modules are installed on membranes in direct contact with water, it is not necessary to leave space between the PV modules and the float (floating membrane), since the modules are cooled by direct contact of water with the membrane.

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5.5.3 Performance criteria for floats supporting inverters/combiner boxes

The floats for inverters/combiner boxes shall provide adequate buoyancy and stability, taking into consideration: the higher permanent loads, expected maintenance loads and other variable forces as defined in [4.3].

The floats shall not overturn under any expected loads or moments.

The floats shall be designed to ensure that wave overtopping does not impact operation of the equipment, see Sec.8 for requirements for electrical components, including ingress protection (IP). The floats shall have adequate freeboard to overcome waves or wake effects that may be expected, unless submersion of equipped is considered and designed for as ULS, see [5.4.3.2].

The floats shall have stability to ensure optimal performance of the inverters.

Guidance note:

The selection of appropriate inverter should take into consideration the impact of hydrodynamic forces on the power equipment and the expected stability of the platform for a given location.

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To ensure unrestricted maintenance activities on the float the performance criteria are as follows:

1) Cable termination should be within arm’s reach and visible.
2) Component and floats shall be replaceable with tools available to the maintenance personnel.

The floats shall ensure that the all cables (DC and AC) are not bent beyond their design limits.

5.5.4 Performance criteria for floats supporting transformers

The floats for transformers shall provide adequate buoyancy and stability, taking into consideration the highest permanent loads, expected maintenance loads and other variable loads as defined in [4.3]. In case the transformers are required to be placed on stand-alone floats, the transformer floats shall have sufficient buoyancy (i.e. not be reliant on surrounding network of floats for buoyancy support).

The floats shall be capable of withstanding thermal loads from the transformer in the operational condition. The float design shall take into consideration the maximum operating temperature as specified in the manufacturer’s specification of the transformer to assess suitability against thermal loads.

The maintenance loads shall take into consideration the maximum number of personnel required to perform maintenance and loads that may be transferred as a result of unit replacement in the case of redundancy. The float shall be designed and located to enable transformer replacement during FPV operation, in case of transformer failures.

The platform size on the float shall be sufficient for all maintenance activities, including external maintenance of housing of the transformer.

The floats shall have stability to ensure optimal performance of the transformer. The floats shall be stable enough to ensure the structure housing the transformer or the transformer itself is not damaged when maximum motions are experienced by the float, including the forces generated by these motions.

The transformer floats may require separate mooring to ensure adequate stability of the platform.

Guidance note:

The selection of appropriate transformer should take into consideration the impact of hydrodynamic forces on the power equipment and the expected stability of the platform for a given location.

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The floats shall allow for sufficient movement at the point of entry onto the platform to minimise stress on the cable. The angle and direction of entry of the cables onto the floats shall take into consideration the expected loads on the cables, including hydrodynamic loads.

Entry from underneath the floats may be considered in the instance of submerged cables.

5.5.5 Performance criteria for floats supporting cable trays/cabling

The floats supporting cabling shall ensure that the cables are secure and protected from mechanical and environmental wear. If the cables are not to be ducted, the floats shall provide an adequately covered channel for cables to be laid on an FPV system.

The floats shall ensure that the cables are not bent beyond their design limits. The floats shall allow for some movement of the cables at points of float interconnection. The amount of slack (free movement of cables) should depend on the maximum motion expected at interconnection under maximum expected forces.

The cable covering, when present, shall be removable to provide access to the cables where required.

5.5.6 Performance criteria for floats supporting walkways

The floats for supporting walkways shall provide adequate buoyancy and stability, taking into consideration the loads from maintenance personnel, maintenance equipment that may be used and loads from additional PV components. The buoyancy of the float shall be sufficient to ensure that maintenance personnel does not risk unintentional contact with water.

The floats shall be stable enough to ensure that maintenance personal can safely operate on the FPV system.

The floats platform shall be wide enough for a single person to safely walk on the platform. The floats shall provide a levelled platform for maintenance personnel to carry out any works.

Guidance note 1:

The floats may be designed to provide a platform for tools and equipment and/or components which may be required by maintenance personal.

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The floats shall provide a platform with access to all key equipment which requires periodic inspection and maintenance, including, but not limited to: PV modules, inverters, combiner boxes, monitoring equipment and transformers.

The floats shall provide sufficient space to evacuate one maintenance worker with the use of stretcher from the FPV array. The floats shall also provide sufficient space for fire services to access the FPV array in case of an emergency.

Guidance note 2:

The amount of sufficient space for fire services may be region specific and may require agreement with local fire services. See [11.2.5] for fire safety considerations.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

The floats shall provide anti-slip area to minimise the risk of slip incidents, see [11.2.7] for further details on safety considerations of walkways.

5.5.7 Performance criteria for floats supporting mounting structure

The floats supporting the mounting structure shall provide adequate buoyancy and stability to ensure that walkways and electrical components which are not designed to be submerged do not come into contact with the water body. The floats shall be able to transfer loads from mounting structure without failure of joints or members of the mounting structure.

The level of deformation of the floats caused by the loads shall not damage the mounting structure and shall not place excessive loads on the PV modules.

Guidance note 1:

Calculations detailing the impact of float deformation may be required to verify.

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Floats and supporting structure shall have an acceptable maintenance strategy.

Guidance note 2:

An example strategy could be that all small components are visible for inspection and replaceable without impacting the functioning of surrounding floats. The large components (e.g. those supporting multiple PV modules) could either be replaceable without impacting the function of surrounding floats or designed to be sufficiently robust (e.g. with increased corrosion allowance/design factors) that replacement is unlikely in FPV system’s lifetime. For large components, replacement may still be possible but may temporarily impact the functioning of surrounding floats.

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5.5.8 Performance criteria for floats connecting to mooring system

The floats supporting connection with the mooring system shall be adequately designed to withstand and transfer the large forces expected as a consequence of the mooring system arrangement. Further details are provided in [6.2.3.5].

Guidance note:

Multiple floats may be used to distribute the forces. Spreader bars may be used to distribute the high forces from the mooring connection to the FPV system.

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The floats shall have adequate buoyancy and could be submerged under vertical load from the mooring connection by design, provided that the electrical components of the FPV array are not submerged and the accessibility is maintained.

Further requirements on the interface of the floats and mooring system are discussed in [6.2.3].

5.5.9 Performance criteria for floats interconnections

The interconnections at the floats shall not fail when experiencing maximum forces expected over the lifetime of the structure.

The interconnection shall be durable for its lifetime and suitable for use in marine environment. The components at interconnection shall be accessible and replaceable.

The interconnection shall be durable to withstand the mechanical wear from cyclic motion expected due to expected loads, including hydrodynamic, wind and maintenance loads.

5.6 Material requirements

The objective of this section is to specify the minimum requirements for the material(s) used for floats and float interconnections in an FPV system.

The materials used as floats in an FPV system shall comply to the following requirements:

- Impact strength: float and float interconnections shall be able to resist shocks or impacts that could be expected during installation or during operation, e.g. from floating debris, from docking boats or from rocks on reservoir beds.
- Tensile strength: materials for floats and float connections shall have sufficient long-term tensile strength to withstand the expected loads for the expected lifetime.
- Durability: floats and float interconnections shall be durable for their lifetime, for the expected design stresses.
- Resistance to degradation (UV and Thermal): floats and float interconnections shall have sufficient resistance to UV and thermal degradation over time to ensure that the floats can fulfil the respective performance criteria in [5.5] during operation.
- Fire resistance: floats may need to be resistant to fire in certain use cases. See [11.2.5] for fire safety considerations.

Guidance note 1:

Depending on the level of fire risk, particular consideration may be required on the design of the floats to ensure that fire propagation is limited in the case of fire. Additionally, use of floats with flame retardant additives may be considered, if not harmful for the environment according to an ESIA assessment, see [7.3.3].

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- Non-toxicity: floats and float connections shall not release toxic materials into the water body during any stage of an FPV system (i.e. installation, operation or decommissioning). Float interconnections are expected to be in constant motion. The interconnection (including any fasteners) shall not release micro-plastics or any harmful substance into the water due to wear.
- Recyclability: floats and float interconnections are recommended to be recyclable at the end of the system life. See Sec.10 for considerations on decommissioning and recycling.
- Shear strength: the float interconnections (including any fasteners) shall be able to withstand the maximum shear forces expected.
- Corrosion resistance (metals only): any metallic components which may be incorporated into floating structure (structural framework, PV module clamps or fasteners) shall have appropriate corrosion resistance to last for the lifetime of the FPV system. If multiple metal structures are present, adequate protection against galvanic corrosion shall be considered.

Guidance note 2:

Steel, aluminium or ferrocement may be used for floats, particularly for instances where functional requirements and performance criteria in [5.3] and [5.5] respectively are not fulfilled. Use of such material may impose additional requirements, e.g. concerning corrosion.

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5.7 Testing requirements

5.7.1 General

The testing requirements for floats are categorised into three levels. These are:

- Testing requirements for the materials: tests demonstrating mechanical attributes of the materials making up the floats.
- Testing requirement for floats: tests to demonstrate structural and mechanical attributes of complete floats and interconnections.
- Testing requirements for floating platform: tests demonstrating structure integrity of all floats making up FPV system.

5.7.2 Testing requirements for the material

5.7.2.1 General

The testing requirements for the materials making up the floats and floating structure in the subsections below are based on the material requirements set out in this RP, see [5.6] for details. It is noted that the tests recommended in this subsection are based on a sample of the final material to be used for the floats, unless stated otherwise. The dimensions and shape of the sample shall be as prescribed in the relevant testing standards.

The standards listed in this subsection are examples of applicable relevant standards for specific materials. Alternative local or international standards may be referred to, if applicable and relevant to the material being tested and the properties to be tested.

5.7.2.2 Test for impact strength

In case of polymer material, impact strength of the material shall be tested according to ISO 179-1:2010 Plastics - Determination of Charpy impact properties - Part 1: Non-instrumented impact test, or according to ISO 180: Plastics - Determination of Izod impact strength.

In case of other materials, relevant equivalent standards shall be used for testing.

Guidance note 1:

There are alternatives to these international standards that may be used to assess the impact strength of the materials: ASTM D256 and ASTM D6110.

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The results from impact testing are critical in understanding how much force a material will be able to withstand before complete failure. The impact strength of a given component shall be sufficient for the ALS specified for that component, see [5.4.3] and [4.2.3] for details on ALS.

Guidance note 2:

Impact strength for steel products may be identified using tests in EN 10045-1.

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5.7.2.3 Test for tensile strength

In case of polymer material, tensile strength of the material shall be tested according to ISO 527-1:2019 Plastics - Determination of tensile properties.

In case of other materials, relevant equivalent standards shall be used for testing.

Tensile strength for steel products may be identified using test in EN 10002 -1.

The short term and long term tensile strength, see [5.7.2.4] below on durability, of the material used for a given component shall be sufficient for the ULS specified for that component, see [5.4.3] and [4.2.3] for details on ULS.

Guidance note:

Alternative standard that may be used for testing tensile strength of polymer material is ASTM D638.

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5.7.2.4 Test for durability

The test for durability of the material shall be able to characterise long term performance under load. One way to assess durability is to assess creep within polymers.

Guidance note 1:

Creep may occur under the influence of constant stress, as applied through tensile, compressive, shear, or flexural loading. It occurs as a function of time through extended exposure to levels of stress that are below the yield strength of the material.

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In case of polymer material, creep tests shall be carried out according to ASTM D2990 - 17 Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics.

In addition to creep, the resistance of the material to crack under stress is a good indicator for durability. The material shall undergo chemically accelerated stress cracking test according to ASTM D1693 – 15 Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics.

In case of other materials, relevant equivalent standards shall be used for testing.

Guidance note 2:

ASTM D1693 -15 is specifically for Ethylene plastics. Similar stress cracking tests may be carried out for alternative floating materials. The standard ISO 22088 Plastics — Determination of resistance to environmental stress cracking (ESC) is applicable to wider range of plastics.

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Guidance note 3:

It is recommended that HDPE is not exposed to oxidising agents, e.g. hydrogen peroxide and halogens, as they are considered corrosive and may have a detrimental impact on physical and mechanical characteristics.

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5.7.2.5 Test for degradation (UV and thermal)

UV degradation

Polymers including HDPE, being considered for use as floats in FPV system shall undergo accelerated UV testing. The following two options may be considered:

- ISO 4892-3: 2016 (4th edition) – Test carried out using Fluorescent UV lamps. May be used to simulate the spectral irradiance of global solar irradiation in the short wavelength UV region of the spectrum.
- ISO 4892-2: 2013 – Test carried out using Xenon arc lamps. Xenon arc lamps when fitted with filters, is used to simulate the relative spectral irradiance of daylight in the UV and visible regions of the spectrum.

Translating the hours of testing using the above standards to relative durability of the floats in real-life conditions is currently not achievable. This document will be updated if there are further developments on this matter.

Guidance note 1:

Other testing procedures that may be used to replicate weathering conditions include ASTM G154, ASTM G155 and EN 16472:2014.

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Guidance note 2:

Accelerated UV testing using one of the test procedures discussed above may be carried out for a minimum period of 2,000 hours.

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At least 3 samples shall be tested for a period of time representative of the expected life of the floats, see guidance note 1 and guidance note 2, for the following tests:

- Tensile Strength – ASTM D638, see [5.7.2.3] for details
- Impact Strength – ISO 180, see [5.7.2.2] for details
- Hardness – ISO 868
- Fire resistance, see [5.7.2.6] for details.

Samples exhibiting < 5% change in physical properties after the required duration of UV testing may be considered to demonstrate robust UV resistance. The change in physical properties of the sample shall not affect the functional requirements and performance criteria for the respective floats in [5.3] and [5.5] respectively. The change in physical properties after UV testing should be determined and reported.

Guidance note 3:

Tests and assessment may be carried out to correlate chemical reactions occurring in the sample floating material against physical changes in the sample material. The creation of oxidised product is an example of chemical parameter which may be assessed.
If the chemical reaction is representative of ageing, then mechanical tests listed above may not be required and the ageing performance of the sample of floating material may be determined by the level of oxidised products created.

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In case of other materials, relevant equivalent standards shall be used for testing.

Guidance note 4:

Polymers such as HDPE undergo photo-oxidative degradation during the course of their life (caused by action of UV in the presence of oxygen). Use of UV absorbers and/or stabilisers is shown to increase the durability of HDPE under accelerated testing conditions. These additives may be considered as a solution, depending on the location and expected operational life of given use case.

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Thermal degradation

The accelerated tests for UV degradation, discussed above, take into account the impact of thermal degradation on the materials to be used in floats. The temperature ranges noted in these tests are considered representative of real-life conditions and additional assessment for thermal degradation is not necessary.

Guidance note 5:

The following test may be carried out to assess the thermal characteristics of polymers, such as HDPE; ISO 11357-6: Plastics — Differential scanning calorimetry (DSC) — Part 6: Determination of oxidation induction time (isothermal OIT) and oxidation induction temperature (dynamic OIT)

The differential scanning calorimetry test, under ISO 11357-6, is useful in assessing the oxidation stability of the material. A material with longer isothermal OIT may be considered to have a better short term oxidation stability however, it may not necessarily translate to better long term stability.

It is noted that anti-oxidative additives, which deliver good OIT results could mask poor long-term performance in terms of oxidation stability of the material.

The melting temperature of the material and other thermal properties of HDPE may be determined using DSC.

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In case of other materials, relevant equivalent standards shall be used for testing.

5.7.2.6 Test for fire resistance

HDPE is a flammable material, which when exposed to open flame may melt, drip and potentially propagate fire. Under certain conditions, fire resistant materials may need to be used, see [5.6] for details.

Guidance note:

Flame retardants may be used as additives to decrease the flammability of the floats, if not harmful for the environment according to an ESIA assessment, see [7.3.3].

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Flammability and burning characteristics of the floats should be assessed using the following relevant standards and the test within:

- UL 94 Standard: Tests for Flammability of Plastic Materials for Parts in Devices and Appliances
- IEC 60707: Flammability of solid non-metallic materials when exposed to flame sources
- ISO 9773: Plastics — Determination of burning behaviour of thin flexible vertical specimens in contact with a small-flame ignition source
- ISO 9772: Cellular plastics — Determination of horizontal burning characteristics of small specimens subjected to a small flame
- ASTM D635: Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position
- ASTM D3801: Standard Test Method for Measuring the Comparative Burning Characteristics of Solid Plastics in a Vertical Position

In case of other materials, relevant equivalent standards shall be used for testing. The requirement for the flammability of the floating material depends on the result of the fire risk assessment carried out for a given FPV project, see [11.2.5] for further details. If so required, the material shall be tested to ensure it is not flammable according to relevant standards.

5.7.2.7 Test for non-toxicity

The material shall be tested for leaching of substances that may be harmful to humans or the environment, including: heavy metals, toxic materials or micro plastics. The material shall be tested in accordance with relevant regional standards and/or regulations and in accordance with testing standard for that specific material.

Guidance note:

Additional test to assess leaching of toxic materials may be carried out for all materials making up the FPV array.

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5.7.2.8 Test for corrosion resistance

The following factors shall be considered when assessing the impact of corrosivity on metal frameworks, clamps and fixings:

- level of relative humidity
- salinity of the water body (systems in sea water are expected to be in corrosive environment)
- design of the floats (clearance from the water level)
- height of maximum wave expected (this may lead to splash zones on the frames).

Finishing of all metal components shall be compatible with different levels of corrosion resistance according to ISO 12944-2. ISO 1416 and EN 10346 shall be considered for galvanizing of steel structures.

Guidance note:

The frames which are installed in highly corrosive environments may require highly protected finishing to prevent corrosion. ISO 12944-2 standard distinguishes sites into various corrosion categories from mild to extreme. Additional corrosion protection may be required for more severe environments, such as coastal areas or environmentally contaminated areas. Local conditions should be considered to ensure adequate corrosion protection.

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5.7.3 Testing requirements for floats

The following mechanical testing for individual floats and float interconnection shall be carried out prior to installation of the floating structure.

- Bending test for subassembly of floats and interconnection: the degree of bending at the interconnection shall correspond to the wave heights expected, see [2.3.5] for details. The number of cycles shall be greater than the frequency of waves expected in the lifetime of the system, see [2.3.5] for details. The period of the cycles may be short (i.e. 5-10 seconds) to accelerate the testing. The bending test shall be set up to avoid dynamic affects. The frequency domain selected for the bending test shall ensure that self-heating will not modify the test results.
- Compression and tension tests of the floats: the floats shall be tested for maximum tensile strength (before breakage) and compressive strength to test the force required to deform the floats under compression.
- Tension tests on subassembly of floats and interconnections: the maximum tensile strength of subassembly shall be tested. The maximum tensile strength of the subassembly shall be recorded when first breakage in any of the float/interconnection occurs.
- Tension tests of the interconnecting elements: the interconnection elements (whether they are plates with fasteners or latch mechanism) shall be tested to identify maximum tensile strength.
- Shear strength for fasteners (if applicable): the shear strength shall be tested in accordance with relevant standards. ISO 3597 should be referred to for reinforced plastic and ASTM D5379 should be referred to for composite materials.

Guidance note:

These tests do not require the floats to be loaded with equipment (e.g. if floats supporting PV technology are being tested, the PV modules are not required to be mounted on the floats).

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5.7.4 Testing requirements for FPV array

The testing requirements for global performance testing of FPV system, including the mooring system, may be found in [4.5.5] including requirements for model and pilot testing of FPV systems.

The testing methods for determining wind force and pressure coefficients are discussed in [4.4.2.4] and the modelling of environmental loads is discussed in [4.4].

Prior to commissioning and connection with the mooring system:

- The floats of the FPV array shall undergo visual inspection to verify integrity of the system (ensuring there are no deformations of the floats).
- The interconnections shall undergo functional testing. The interconnections may be tested using pre-tensed winches (in line with design limits).

SECTION 6 ANCHORING AND MOORING

6.1 General

This section provides requirements, recommendation and guidance for station keeping for FPV systems.

Herein, the station keeping system refers to the mooring system, consisting of mooring lines which are attached to the floating structure at one end and anchored to the waterbed or the bank at the other end, and the anchors. In principle, station keeping could also be provided by dynamic positioning or fixed structures (e.g. piles and rollers) restraining horizontal motions of the structure. Requirements for these types of station keeping systems are not specifically addressed in this section.

The station keeping system shall keep the horizontal excursions of the FPV array within acceptable levels. This shall allow for the intended operation, keeping a safe distance to shore, any obstacles or other infrastructure, and to maintain the integrity of any connected structures or components. The station keeping system is vital for keeping the floating structure in position such that the FPV array can maintain generation and transfer of electricity. It can also be vital for avoiding dislocation of floats and to limit stress concentration in float connections.

Unless otherwise specified, all structural components in the station keeping system of the FPV system shall be designed to consequence category 1 as specified in [4.2.1.2]. This requirement refers to station keeping systems which have redundancy, or in situations where a free drift of the FPV array will not pose a risk of collision with any adjacent structures.

For station keeping systems without redundancy and in situations where a free drift of the FPV array will pose a risk of collision with any adjacent structures, all structural components in the station keeping system shall be designed to consequence category 2 as specified in [4.2.1.2].

Guidance note:

Redundancy is defined as the ability of a component or system to maintain or restore its function after a failure of a member or connection has occurred. Redundancy of a mooring system implies that the system has reserve capacity in case a failure occurs and one (or several) mooring line(s) and/or anchor(s) are lost. The quantitative minimum requirements for what the reserve capacity should be, in order to qualify the intact undamaged system as having redundancy, are provided in [6.2.4] and [6.3.2].

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Design of overall mooring system, including mooring lines, is addressed in [6.2].

Design of anchors is addressed in [6.3].

6.2 Mooring system design

6.2.1 General

This subsection covers mooring system design, which herein is defined as all the components in the mooring line excluding the anchors.

6.2.2 Mooring system arrangement

6.2.2.1 General

A mooring system arrangement, i.e. configuration, layout and number/type of lines, shall be designed with the intention of keeping the horizontal excursions of the FPV array within acceptable levels.

Guidance note 1:

This is achieved through restoring forces and moments from the mooring system on the FPV array, pulling the structure back towards its equilibrium position and hence limit the horizontal range in which the structure is allowed to move. The restoring force depends on the geometric and axial stiffness properties of the mooring lines which depend on how the mooring system is arranged (configured) and which material the lines are composed of. The mooring lines may be evenly spread around the perimeter of the installation, or they may be clustered (group of several lines installed with small spacing between adjacent lines) to optimize the design against the prevailing environmental direction.

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The following site condition factors, most of which defined in Sec.2, shall be taken into consideration when designing the mooring system arrangement:

- topography
- soil conditions
- bathymetry
- water depth
- water level variation
- environmental conditions
- marine growth.

In addition to the site condition factors, functional and performance requirements defined for the FPV system shall be considered.

The mooring system and anchors shall be designed such that the total capacity is adequate to withstand the extreme and cyclic environmental actions accounted for in design, with adequate margins according to the defined load and material factors, see requirements in [6.2.4], [6.2.5] and [6.3.2].

Guidance note 2:

The number of mooring lines required to achieve this will vary significantly across systems mainly depending on the size and structural design of the FPV system, the environmental conditions at the site, the holding capacity of each line and requirements to maximum horizontal motions.

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The main configurations of mooring lines applicable for FPV systems include:

- submerged mooring
  - catenary mooring
  - taut leg mooring
- shore mooring
- hybrid of submerged and shore mooring.

Guidance note 3:

If the FPV system is installed close to shore at one or two sides, it would in most cases be beneficial to have shore mooring on these sides, while submerged mooring is used on the water-facing sides.

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Further details on different types of mooring system configurations may be found in ISO 19901-7:2013 Annex A.

Guidance note 4:

For FPV systems with mooring system arrangements similar to conventional systems known from the aquaculture and fish-farming industries, guidance may be found in NS 9415.

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6.2.2.2 Load distribution

The mooring system shall be designed and installed to ensure redundancy, i.e. the failure of one mooring line shall not lead to progressive failures of several mooring lines.

Guidance note:

A relatively large number of mooring lines (up to several hundreds) with relatively low holding capacity per line is currently widely used for FPV systems. The advantage of having many mooring lines is that it will allow distribution of the loads along the floating structure and to preserve buoyancy of the floats. A potential risk is that the loads will not be evenly distributed between the individual mooring lines. In such cases, the mooring line or anchor taking the largest load could well exceed the capacity and break. Consequently, other lines will take even larger loads and one would risk multiple line failures or progressive collapse of the mooring system and damage to the installation as a worst-case scenario.

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The mooring system shall be balanced, with mooring line pretensions as evenly distributed as is practical. The following measures shall be considered:

- Tolerances regarding line lengths and anchor installation positions shall be defined and confirmed by post-installation survey, see [9.2.3]. The design analyses shall envelope these tolerances.
- Mooring lines connected to the same side of the floating structure should as far as practically achievable be symmetrically configured. If using split lines (one main mooring line connected to the anchor, split in several lines connected to the float) angles shall be optimized to ensure an even load distribution within the split.
- Adjacent lines should have the same properties in terms of length and axial stiffness, and should preferably be from the same manufacturer. Systems with shorter lines are more prone to tension variations due to the larger relative effect from anchor installation tolerances on the line tension.
- The effect of creep in line material shall be accounted for in design if relevant.
- The mooring design shall aim to provide more even tension distribution between individual lines. This may be done by use of elastic elements or clump-weights/buoyancy elements, see [6.2.3.6] and [6.2.3.7] respectively.
- Sensitivity checks shall be carried out in the ULS to document robustness to tension variations between individual lines.
- For shore mooring systems with short lines and asymmetric mooring arrangement, particular attention shall be given to the assessment of the potential uneven load distribution.
- It is generally recommended to carry out fully dynamic analyses for systems which are prone to uneven load distributions. If static analyses are carried out, the accuracy of the results shall be justified.

For mooring of floats with limited buoyancy, care should be exercised when designing the mooring system and means for reducing the vertical mooring load component on the floats, e.g. by use of buoyancy elements or long mooring lines should be considered.

6.2.2.3 Water level variation

The mooring system arrangement shall be designed to maintain station keeping capabilities throughout the whole range of water levels relevant for the site.

Guidance note:

Water bodies with large variation in water level are challenging with respect to mooring as the change in water level will alter the geometry, and subsequently the restoring force, of the mooring lines. Up to 30m and beyond water level variation may be expected at certain sites such as hydro dam reservoirs. For submerged lines, increased water level will tighten the lines while reduced water level will slacken the lines. Shore lines will normally have the opposite effect. Too tight lines may pose a risk to the integrity of the mooring system while too slack lines will fail to limit horizontal excursions of the FPV array.

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The following measures shall be considered for sites with large variations in water levels:

- Use of longer lines, i.e. increased horizontal distance between the floating structure and anchor position, which can accommodate water level variations while minimizing the change in the geometry of the lines.
- Use of buoyancy elements that can absorb water level variation while maintaining the catenary profile of the lower line. This will reduce the risk of waterbed abrasion.
- Use of elastic elements in the mooring lines which will elongate and retract to maintain station keeping capabilities throughout a wide range of water levels.
- Use of fixed piles and rollers along the perimeter of the structure to allow free vertical motion and restrict horizonal motion.

- For smaller, shore-moored FPV systems, use of hinged mooring booms may provide a simple control of the structures position during large water level variations.
- For planned water level variations, e.g. in hydro dam reservoirs, mitigations and adjustment to the mooring system may be implemented and shall be planned and described in an operation manual.

6.2.2.4 Additional requirements to shore mooring systems

Shore mooring involve mooring alongside the bank, a pier, a quay, a jetty or other floating or land-based infrastructure.

Guidance note:

Shore mooring systems are often used in cases where the floating structure is installed near the bank/shore, and for cases where submerged mooring may be challenging, e.g. due to environmental considerations or waterproofing. The mooring lines may be completely suspended in the air or partly in contact with the water surface. Spring lines are installed in-line with the float to limit longitudinal motions, while breast lines are installed perpendicular to the float to limit transverse motions.

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The following considerations shall be made when using shore mooring systems. More details and recommendations may be found in DNVGL-ST-N001 App.Q.

- It is recommended that the vertical angle, measured up from horizontal plane, is minimized, and it should not exceed 25 degrees.
- Lines shall be arranged as close to normal to the FPV side plane as practically possible, in order to be effective. Parallel lines shall be as close to equal length as practically possible. If using fibre ropes, parallel lines shall have equal stiffness characteristics.
- Variation in water level shall be accounted for. Risk of chafing and abrasion due to water level variations shall be avoided or mitigated with protection measures.
- Systems using adjacent mooring lines of different length and axial stiffness are prone to uneven load distribution. It shall be avoided as far as practical.
- Mooring lines shall allow the floating structure to be compliant enough to allow float motions in waves or due to the wake from passing vessels, if relevant.
- Sufficient clearance between the floating structure and the bank shall be ensured for all relevant environmental conditions at the site. Use of fenders may be considered. Project specific clearance requirements shall be clearly stated in the design documentation.
- Measures for limiting peak loads shall be considered, especially for systems with short lines. Use of low stiffness fibre ropes (e.g. nylon) or elastic elements may be considered.
- For reservoirs with waterproofing systems, the shore anchor points shall be installed at a safe distance from the waterproofing system and any interference shall be avoided.
- Implications for boat access shall be evaluated. Measures for reducing risk of external impact shall be implemented based on a risk assessment.

6.2.3 Mooring lines

6.2.3.1 General

Each mooring line is often composed of several segments or components with different properties. All components in the mooring system shall function as intended throughout the service life of the FPV system. The following components may be part of the mooring line assembly:

- mooring line material such as fibre rope, chain or steel wire cable
- connecting elements such as shackles, links, connecting plates, fittings, etc.
- mooring line segments, inserts and accessories such as elastic elements, buoyancy elements, clump weights, etc.

When selecting components, it is important to assess factors such as strength, stiffness, durability, degradation, installation and maintenance and compare those properties to the cost-, design- and functional requirements of the system. Different types of components will have advantages and disadvantages which needs to be evaluated against the requirements for each specific system. It is of vital importance that the individual components in the mooring line match one another, e.g. no adverse effects such as galvanic corrosion shall be introduced from one component to the next, and end terminations and connecting elements shall be suitable for the elements they are connecting.

The key properties of all individual components of the total mooring system arrangement shall be documented and kept throughout the service life of the FPV system. It is recommended to use certified mooring components that shall be documented to be tested by the manufacturer or by an independent party. Tensile test and cyclic load tests shall be carried out as a minimum. Records of testing shall be obtained and kept.

The strength of the mooring line components (MBL) shall be stated in the product certificates issued by the manufacturers. For components prone to degradation due to corrosion or reduced strength due to water absorption, the reduced strength shall be accounted for in design.

Line length tolerance shall be defined.

Sufficient clearance shall be ensured to avoid interference between:

— Individual mooring lines during cross-anchoring.
— Mooring lines and other structures or obstacles.
— Mooring components and other parts of the FPV system (clashing).

If contact is unavoidable, it shall be demonstrated that the contact will not cause any damage.

Wear of mooring line components may be a challenge and shall be addressed in the design phase. Risk of chafing and abrasion shall be minimized as far as practically possible.

Mooring line bearing angles shall be assessed to avoid out-of-plane loads on components with limited rotation angles. Tolerances regarding line angles shall be defined based on the relative displacement of the array and resulting angle of the mooring line. For the design of the mooring point, the out-of-plane component should be at least 5% of the main line load to take into account potential unintended out-of-plane forces.

In addition to the aspects covered in [4.5], the following factors shall be accounted for when carrying out design analyses to determine the loads in the mooring lines:

— For submerged lines, the effect of marine growth in terms of increased weight and drag diameter shall be accounted for. Values for fully developed marine growth shall be applied.
— The applied software and station-keeping model shall be able to properly represent the stiffness characteristics and change-in-length performance of all the components composing the mooring system. E.g. Non-linear force-elongation relationship, hysteresis effects, etc. It shall be demonstrated that conservative assumptions are applied.
— The weight and buoyancy of all mooring line components shall be accounted for in the analysis. The effect of mooring line dynamics, i.e. inertia and drag forces acting along the length of the mooring lines, shall be considered if relevant.
— The effect of the defined tolerances regarding line lengths, line angles and anchor positions shall be enveloped in the analyses.

See [9.2.3] and [9.3.3] for guidance regarding respectively installation and O&M of mooring lines and their components.

6.2.3.2 Chain

Chains are commonly used in mooring systems, both as chain-only systems and in combination with other line materials. Chain for use in water are produced in different grades with associated ultimate tensile strength. Factors such as required strength, weight, corrosion and cost should be considered when selecting the chain grade.

Corrosion allowance, including wear and tear of chain and its connection elements shall be included in design and MBL shall be taken as the end-of-life MBL. Ideally, corrosion rates relevant for the actual site should be used for defining the corrosion allowance.

For further details regarding mooring chains, see API Spec 2F.

6.2.3.3 Steel wire cable

Steel wire cables may be applied alone or in combination with other line materials.

Guidance note:

Steel wire cables for mooring system applications may be stranded ropes or spiral strand rope:

- The stranded rope is composed of multiple strands that are wounded in the same rotational direction around a centre to form the wire rope. The number of strands and wires in each strand will govern the strength of the steel wire cable.
- The spiral strand rope is composed of a number of wire layers which are wound in opposing directions and have high load capacity relative to nominal diameter.

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The steel wire cable may be sheathed for increased corrosion resistance.

The steel wire cable is sensitive to abrasion due to friction with the waterbed or bank. Design measures to increase the abrasion resistance shall therefore be considered.

For further details regarding steel wire cables, see DNVGL-OS-E304.

6.2.3.4 Fibre ropes

Different types of fibre ropes are commonly applied in mooring systems. An overview of some common types of ropes applicable for FPV systems and their characteristics are given in Table 6-1. Note that the values are indicative only and may vary significantly from one manufacturer to another.

Table 6-1 Characteristics of fibre rope material

	Nylon	*Polyester*	*Polypropylene*	*HMPE / UHMWPE*	*LCP*	*Aramid*
Tenacity (g/den)[1]	7.5 – 10.5	7.0 – 10.0	6.0 – 7.0	40.0	23.0 – 26.0	28.0
Elongation[2]	15% – 28%	12% – 18%	18% – 22%	3% - 4%	3% - 4%	4% - 5%
Mass density (g/cm^3)	1.14	1.38	0.91	0.98	1.40	1.39
Coefficient of friction	0.12 – 0.15	0.12 – 0.15	0.15 – 0.22	0.05 – 0.07	0.12 – 0.15	0.12 – 0.15
Critical temperature[3]	163 °C	177 °C	121 °C	65 °C	148 °C	271 °C
UV resistance	Good	Excellent	Fair	Excellent	Limited	Limited

[1] Measurement of the ultimate tensile stress of the fibre in grams per denier.

[2] Percent of fibre elongation at break, including permanent and elastic elongation.

[3] The point at which degradation is caused by temperature alone.

Guidance note 1:

In addition to the fibre material, the rope construction is of importance with regards to the rope properties. The strand is the principal component of a rope or subrope. It is formed by an assembly of yarns which are grouped together. Fibre ropes may be manufactured with a braided, helical or parallel arrangement of the strands. The built-in twist of the strands depends on the production method. A bundle of many parallel, load-bearing elements with an external jacket may also be used. Those parallel elements may be braided or helical subropes, or large (assembled) yarns.

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Values based on the wet characteristics (strength and stiffness properties) of fibre ropes shall be applied in design assessments.

The 3-T (time-tension-temperature) endurance of the fibre rope shall be considered in design. 3-T is the load bearing capability of the yarn material over time in response to tension and temperature. The criticality of each parameter depends on the other two parameters. It is recommended that the 3-T performance characteristics are established by testing. Specific operational experience should be fed back to refined O&M procedures and improved design procedures.

Guidance note 2:

The feedback of operational experience could be achieved through collecting samples of fibre rope that has been in operation. Intervals for collecting samples, i.e. every N months, may be defined in the O&M procedures. Testing of stiffness and strength may be carried out to gain insight regarding the site specific degradation of the ropes.

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The effect of creep (and other change-in-length performance) shall be documented by testing and accounted for in design. Creep is the time- and tension-dependent elongation due to stretching of the polymer in a fibre rope. This will imply a relaxation of the tension in the rope over time. Creep and its associated relaxation form a separate load case and shall be addressed in the design of mooring systems containing fibre rope. For this purpose, the creep and its associated relaxation shall be combined with high or low water level, whichever is more unfavourable. To control the permanent change-in-length it may be beneficial that the fibre ropes are bedded-in, i.e. exposed to a sequence of tensile loading to settle the fibres and their geometry, prior to or after installation.

The following design measures shall be taken when applying fibre ropes:

- Twisting may be caused by variation in torque response to tension between two types of ropes. The fibre rope shall be constructed with similar torque/rotation characteristics as the remainder of the mooring line (torque matched). E.g. torque-neutral fibre rope should be used in combination with torque-neutral wire rope.
- Chafe points shall be avoided.
- Direct contact between fibre rope and the seabed or the bank shall be limited or avoided. This is due to risk of:
  - sear from external abrasion
  - soil ingress and consequently internal abrasion.
- Due consideration during all project phases shall be given to degradation from wear, UV exposure, heat tolerance, water absorption and other environmental and chemical influence. Special care should be exercised if the fibre ropes are directly exposed to sunlight. Rope coating or an external jacket may be used for improving abrasion and heat performance.
- The material- and construction-specific change in strength and weight when exposed to water should be considered.
- Avoid using fibre rope outside the envelope of its intended use, for which it has been qualified and tested for.
- Attention shall be given to the fibre rope end terminations and recommendations from rope manufacturers regarding specific rope and application shall be adhered to.

The elongation and stiffness properties of fibre ropes shall be properly accounted for in the load and response assessment. Guidance for how to implement fibre rope properties in analysis models are provided in DNVGL-OS-E301 Ch.2 Sec.2 [2.1.8].

Further details regarding fibre ropes may be found in DNVGL-OS-E303 and DNVGL-RP-E305.

6.2.3.5 Connection to float

The mooring line attachment point is the point where the loads in the mooring system are transferred to the floating structure through e.g. a shackle on the mooring line connected to an eye or a bar on the float. The strength of the connection elements shall be sufficient to withstand the maximum calculated mooring line loads. This may be achieved by selecting an appropriate connection element, or by designing the mooring arrangement to obtain a maximum load within the strength limit of the attachment point. Resistance to cyclic loading (fatigue) of attachment point components shall be documented, ideally by testing.

The buoyancy of the float(s) and the vertical angle of the mooring lines shall be considered when designing the attachment points. Measures for improved distribution of loads along the float(s) may be considered.

It is normally not required to have systems such as fairlead to control the lateral movement. Lateral forces must therefore be accounted for as relevant in the design of the connection point.

6.2.3.6 Elastic elements

Elastic elements are here defined as in-line elements in taut mooring or shore mooring such as elastic rubber hawsers. They are designed to maintain the tension in the mooring lines within certain limits to avoid slack lines and control peak loads.

By using elastic elements, the load/excursion relationship (mooring line characteristics) will be altered to reduce loads and slightly increase the allowable excursions in the high-tension area. Elastic elements may be used to improve load absorption characteristics, i.e. reducing the vulnerability to peak loads, and to accommodate large water level variations. Fewer mooring lines may be needed with this solution as compared to static materials.

Use of elastic elements may also lead to a system less vulnerable to uneven tension distribution among mooring lines, as raised in [6.2.2.2].

Elastic elements may be used in combination with ropes of relatively high stiffness, e.g. polyester or stiffer. The design shall be optimized to allow tension in all relevant design conditions to be within the working elongation of the elastic elements. Should the working elongation be reached, the stiffer rope will bypass the mooring line loads.

The properties of the elastic elements in terms of material composition, weight, elasticity and hysteresis effect should be obtained from the manufacturer and taken into account in design. The manufacturer shall show documented capacity against cyclic loading as input to fatigue analysis.

6.2.3.7 Other components

In addition to the main material constituting the mooring cable and the elastic element treated separately in [6.2.3.6], other types of components may be used in a mooring system to optimize the performance and serve as connection between mooring line segments. Some of the most common components applicable for FPV systems include:

- Buoyancy elements: to reduce the vertical load on the perimeter float(s), improve clearance to seabed or other obstacles, and reduce peak loads.
- Clump weights: to increase the weight of the mooring line which will increase the restoring force.
- Connecting elements, chain fittings and accessories: to connect mooring line segments/components, ease handling and avoid twisting.

The strength and durability of all components shall be properly assessed and documented.

Guidance note 1:

Note that certain software may have limitations with respect to modelling the material properties. It should therefore be documented that the selected software can accurately represent the physical behaviour of the mooring line components.

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Structural design of the buoyancy elements shall be carried out in accordance with DNVGL-OS-C101. They shall be positioned to not interfere with the floating structure, or other structures or the bank. Loss of buoyancy elements shall not cause mooring line failure or submergence of perimeter floats.

Clump weights shall be positioned to avoid waterbed interference which may damage the clump weight and/or its connection to the mooring line. As an alternative to using one or several clump weights, one may consider using heavier chain.

Connecting elements, chain fittings and terminations shall be designed to have strength exceeding the characteristic strength of the element it is connected to. The fatigue performance shall be documented by testing or analyses.

Guidance note 2:

Note that increasing the number of individual mooring system components and connections will increase the installation complexity and introduce additional failure modes in the mooring system. Limiting the number of components, while meeting the performance requirements would therefore be a recommended design strategy.

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6.2.4 Design for extreme environmental loads (ULS and ALS)

6.2.4.1 General

This subsection provides recommendations on design criteria for extreme environmental loads that may be applied for design of mooring lines for FPV systems.

The design criteria for extreme environmental loads are defined in terms of the ultimate and accidental limit states (ULS, ALS):

- ULS: the intact mooring system and its individual mooring lines shall have adequate capacity to withstand the load effects imposed by extreme environmental actions.
- ALS: the damaged mooring system shall have adequate reserve capacity to withstand the load effects imposed by extreme environmental actions. The system shall not suffer progressive failures of the remaining mooring lines following the initial loss of one mooring line or other failure.

6.2.4.2 Design criteria

General description of the method for design by partial safety are given in [4.2.5]. For design of mooring lines, the load effect in components of individual mooring lines, expressed as design tension T_d, shall not exceed the resistance, here given as the characteristic capacity R_c, of the same component. The design criterion is expressed as:

$$R_c - T_d \geq 0 \tag{6.1}$$

6.2.4.3 Characteristic capacity

The characteristic capacity, R_c, of the mooring line, shall be taken as the minimum breaking load (MBL) of the components in individual mooring lines. For mooring design, the characteristic capacity corresponds to the design resistance as defined in [4.2.5.4].

For fibre ropes, the 3-T (time-tension-temperature) endurance shall be considered, as described in [6.2.3.4], when setting the MBL for design. This shall be supported by testing.

6.2.4.4 Design tension, T_d

The design tension T_d, represent the maximum line tension obtained when the FPV array and its (intact or damaged) mooring system is exposed to the design environmental loads in ULS and ALS. For mooring design the design tension corresponds to the design load effect as defined in [4.2.5.3].

T_d should be taken as the sum of two factored characteristic tension components $T_{c,mean}$ and $T_{c,dyn}$,

$$T_d = \gamma_{mean} \cdot T_{c,mean} + \gamma_{dyn} \cdot T_{c,dyn} \tag{6.2}$$

where:

$T_{c,mean}$ = characteristic mean tension
$T_{c,dyn}$ = characteristic dynamic tension.

γ_{mean} and γ_{dyn} are load factors given in Table 6-2.

The design tension is obtained from a load and response assessment, see [4.5]. The characteristic mean tension $T_{c,mean}$ is defined as the mean part of the line tension and is caused by pretension and mean environmental loads from static wind, current and wave drift (e.g. mean part of the 50-year value of line tension for ULS). The characteristic dynamic tension $T_{c,dyn}$ is defined as the dynamic part of the line tension and is caused by oscillatory wind and wave loads, both low-frequency and wave frequency effects (e.g. dynamic part of the 50-year value of line tension for ULS).

In DNVGL-OS-E301 Ch.2 Sec.2 [2.2], guidance is given on how to apply statistical methods to calculate maximum line tension based on different types of dynamic analysis methods.

For static analyses, see guidance given in [4.5.3].

6.2.4.5 Load factors

The following load factors should be applied for design of mooring lines.

Table 6-2 Load factors for tension in mooring lines

Limit state	*Load factor*	*Consequence Category 1*	*Consequence Category 2*
ULS	γ_{mean}	1.30	1.50
ULS	γ_{dyn}	1.75	2.20
ALS	γ_{mean}	1.00	1.00
ALS	γ_{dyn}	1.10	1.25

The consequence categories are defined in [4.2.1.2].

The load factors are combined with the characteristic mean tension and the characteristic dynamic tension according to Eq.(2) to calculate the design tension.

Note that load and resistance factors recommended in this RP are not yet calibrated specifically for FPV systems, by means of structural reliability methods, to match target safety level in [4.2.1.3]. The load factors are consistent with DNVGL-ST-0119, which is applying the same safety philosophy as in this RP, i.e. the load factors are intended to target a nominal annual probability of failure of 10^{-4} in consequence category 1 and 10^{-5} in consequence category 2. Applying a two-factor format reflects the fact that there are larger uncertainties related to the dynamic part of the line tension than the mean part of the line tension.

6.2.4.6 Maximum offset

The design offset represents the maximum horizontal excursion when the FPV array and its (intact or damaged) mooring system is exposed to environmental loads according to the relevant limit state. The design offset is obtained from a load and response assessment, see [4.5]. The expected maximum horizontal excursion value (mean of max) shall be applied as the design offset and the value should not exceed the project specific limitations. For static analyses, a dynamic amplification factor (DAF) shall be applied.

6.2.4.7 Load cases

Load cases are defined to ensure that the mooring system design takes into account the most unfavourable combinations of mooring system conditions and environmental loads that may be excepted during its lifetime.

It is recommended that all environment directions are assessed, preferably at intervals not larger than 30 degrees. It is important that directions towards the side of the floating structure (in-line) and towards the corners are included. Individual environmental actions (e.g. wind, waves, current) shall be assumed omni-directional and collinear unless site data stating otherwise is available, which then allows for directional design.

Guidance note 1:

For directional design, the location specific directional distributions of wind speed, significant wave height and current speed are applied.

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All relevant environmental actions as defined in [4.3.6] shall be included. They should be combined to a return period of 50 years for ULS and 1 year for ALS (with the exception of the robustness check).

Minimum and maximum water levels shall be checked, in addition to the mean water level. Dominant failure mechanisms will be dependent on water level, e.g. anchor load angle, slack lines, too stiff lines, etc.

Load cases shall be defined to focus on the most critical areas in the mooring system. The critical areas are the areas in the system that are most prone to line failures. This will be the areas around the most utilized mooring lines and corner lines.

Ultimate limit state (ULS)

For ULS, the intact mooring system is assessed. Analyses for the idealised system, i.e. applying the as-designed anchor positions, line lengths and line tensions shall be carried out. All environmental directions and relevant water levels shall be included.

In addition to the idealised system, it is recommended that a sensitivity check is included to document the capability of withstanding uneven tension distributions. The check shall be carried out for critical areas by assessing the most unfavourable combination of tension variation in individual mooring lines based on the design tolerances for line lengths and anchor installation positions. The sensitivity check shall be updated if the post-installation survey indicates that the tolerances assumed in design are not achieved, see [9.2.3].

Guidance note 2:

The critical areas of the mooring system may be identified from the ULS (intact) analyses as the most utilized areas, i.e. lines (and their nearby lines) which experience the highest ratio of design tension and characteristic capacity. Where these areas are located will be highly dependent on the design of the floats, the mooring system arrangement and the directional distribution of the environmental actions. Corners may generally be assumed to be critical areas.

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Alternatively, a simplified check to address robustness to uneven tension distributions may be carried out by simply varying the as-designed pretension levels for individual lines in the analysis model.

Guidance note 3:

The analysis of potential uneven tension distribution may be based on a large number of in-service measurements of comparable mooring systems under comparable environmental loads or an appropriately detailed analytical model including anchor installation tolerances, line tensioning/installation tolerances, line length tolerances, mooring line stiffness (axial and geometric stiffness), water level variations and array lateral and rotational motions.

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The number of lines that should be included in a critical area will be dependent on the overall design and the total number of mooring lines. The selection of critical areas shall therefore be justified.

Guidance note 4:

At least 5 individual mooring lines are recommended to be included in a critical area in order to properly be able to address the effect of uneven tension distributions.

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Accidental limit state (ALS)

In ALS, the mooring system in damaged condition is assessed. Redundancy in the mooring system shall be demonstrated, i.e. that a single line failure will not lead to progressive collapse of multiple lines.

Many FPV systems have a high number of individual mooring lines combined with a limited possibility to continuously monitor the mooring line integrity. These factors increase the likelihood for operating with one or more undetected failed lines, and for some cases it will be a likely scenario during the service life. The methodology used to demonstrate redundancy shall therefore be justified based on the size and design (including number of mooring lines) in the system.

For systems with many mooring lines (above 30), failure in critical areas should be evaluated rather than single line failures. It is recommended to evaluate a 2-lines failure scenario in the critical areas.

Critical areas are defined as for the ULS. For systems with more than 30 mooring lines, it is recommended to define critical areas including ~10 lines adjacent to each of the most utilized lines. For corners, at least the 2 first lines on either side should be included in the critical area. For each critical area, failure of at least 2 mooring lines should be assessed. The utilization of the remaining lines are calculated.

Removal of corner lines shall always be included as load cases in the ALS analysis.

For FPV systems with mooring system arrangements similar to conventional systems known from oil and gas (O&G) or aquaculture structures (e.g. 8-20 lines arranged in a spread or clustered manner), it is recommended to adopt guidance from DNVGL-OS-E301 Ch.2 Sec.2 [2.6.1] for selection of ALS load cases.

For systems with buoyancy elements, loss of buoys shall be included as an ALS check and it shall be documented that the resulting vertical loads on the floats does not exceed the buoyancy. The check shall include loss of all buoys for the most utilized lines. Operational experience from e.g. O&G indicate that in case of failure, multiple buoy failure is likely due to common failure mechanisms.

For systems with specific operational constraints regarding offset (e.g. structure moored in close proximity of another structure), the trajectory of the structure immediately following line failures may be calculated in a transient analysis. Removal of corner line(s) will be most relevant for transient analysis.

In order to assess the non-linearity in the mooring system response characteristics it is recommended to carry out an analysis applying a larger environment return period than for normal ULS conditions. Such a check is often denoted as robustness check. The robustness check is carried out for the intact mooring system applying a 500-year return period on the environmental actions. Sensitivity check for uneven load distribution is not required for the robustness check.

Note that the effect of special events with a very low probability of occurrence, such as earthquakes and extreme accumulation of snow and ice, shall be assessed as separate ALS cases.

Load cases

Table 6-3 provides a summary of the recommended load cases for ULS and ALS.

Table 6-3 Load cases for ULS and ALS

ID	*Limit state*	*System condition*	*Environmental return period*	*Environmental directions*
ULS-1	ULS	As-designed	50 years	0 deg – 360 deg
ULS-2	ULS	Uneven load distribution	50 years	Critical directions from ULS-1
ALS-1	ALS	Critical area failure	1 year	Critical directions from ULS-1
ALS-2	ALS	Corner failure	1 year	Corners
ALS-3	ALS	Loss of buoys	1 year	Critical directions from ULS-1
ALS-4	ALS	Transient	1 year	Corners
ALS-5	ALS	Robustness	500 years	Critical directions from ULS-1

6.2.5 Fatigue design

This subsection provides recommendations on fatigue design that may be applied for design of mooring lines for FPV systems.

Mooring lines shall be designed against fatigue failure if their design life exceeds 5 years. The design criteria for fatigue design is defined in terms of the fatigue limit state (FLS):

— FLS: the mooring system and its components shall have adequate capacity to withstand cyclic loading.

The design cumulative fatigue damage may be expressed as:

$$D_D = DFF \cdot D_C \qquad (6.3)$$

Where D_c is the characteristic cumulative fatigue damage caused by the stress history in the mooring line over the design life, and DFF denotes the design fatigue factor. The design criteria states that the design cumulative fatigue damage D_D shall not exceed the design life of the mooring line.

Recommended design fatigue factors as a function of consequence category are given in Table 6-4.

Table 6-4 Recommended design fatigue factors

Design Fatigue Factor	*Consequence Category 1*	*Consequence Category 2*
DFF	5	10

Dynamic time- or frequency-domain analyses are required to calculate the cumulative fatigue damage D_c. Guidance on how to estimate the cumulative fatigue damage is given in DNVGL-OS-E301 Ch.2 Sec.2 [6].

If relevant, out-of-plane bending of in-chain links shall be accounted for according to DNVGL-OS-E301 and normal industry practice.

6.2.6 Use of other recognized design codes

The load factors, environmental return periods and methods (for mooring design) given herein are corresponding to an intended target safety level as defined in [4.2.1]. Alternatively, the mooring and anchoring system may be designed according to requirements in other applicable and recognized standards or guidelines (e.g. ISO, API, Eurocode, etc.). The complete analysis methodology (load factors, environmental return periods and methods) from the alternative standard or guideline shall then be applied and it shall be justified that the overall level of safety is not less than given herein.

In addition, any regional and national requirements shall be adhered to as applicable.

6.3 Anchors

6.3.1 General

This subsection provides requirements, recommendation and guidance for anchors applicable for FPV systems. Anchors may be installed at the bank for shore mooring lines and/or at the waterbed for submerged mooring lines. In specific locations, depending on the nature of the water body and on local and national regulations, only waterbed anchors or only shore anchoring may be allowed.

An overview of common types of anchors and their characteristics are given in Table 6-5

Table 6-5 Anchor types

Anchor type	*Advantages*	*Challenges*
Gravity-based anchors Holding capacity derived from the weight of the anchor. E.g. concrete or steel blocks	— simple and cheap to fabricate, install and decommission — established design procedures — maintained holding capacity after dislocation (however this may change the load pattern in the mooring configuration) — require least extensive ground investigations — usually accessible for visual inspection — can be used as shared anchoring point	— inefficient design with respect to holding capacity versus anchor weight — sensitive to sliding, most efficient when the entire deadweight of the anchor can be relied upon, i.e. high degree of vertical loading. However, sliding from an isolated event will not lead to a complete loss of anchor holding capacity — require detailed knowledge of bathymetry at anchor position — require ground investigations (least extensive)

Anchor type	*Advantages*	*Challenges*
Embedded anchors I (screw/helical-, earth- and rock anchors) Holding capacity dependent on the anchor type, dimensions, installation method and the properties of the surrounding soil or rock	— high loads can be taken — can be used as shared anchoring point — able to take up vertical, as well as horizontal loads — flexible with respect to soil type and load angles — generally low initial cost — environmentally friendly	— possibly challenging decommissioning — require ground investigations — may have long construction time (for rock anchors) — multi-staged process during installation (for rock anchors) — possibly limited accessibility for visual inspection (if necessary)
Embedded anchors II (driven-, drilled-, suction piles) Holding capacity dependent on the anchor type, dimensions, installation method and the properties of the surrounding soil or rock	— very high loads can be taken — can be used as shared anchoring point — environmentally friendly — noiseless installation for suction anchor — proven technology — able to take up vertical, as well as horizontal loads	— Generally higher costs — possibly challenging decommissioning — require ground investigations — multi-staged process during installation (depending on technology) — possibly limited accessibility for visual inspection (if necessary)
Drag anchors Holding capacity derived from the frictional resistance of the surrounding soil as a function of the embedment depth	— simple to install, especially in case of soft clay — extensive industry experience — may not require to install to ultimate load — easy retrieval/decommissioning	— mostly capable of taking horizontal loads, to limited extent vertical loads — not suitable for shared mooring — not applicable for all soil types and risk of damage due to anchor dragging — possibly limited accessibility for visual inspection — anchor handling vessel required — ground investigation required — possibly challenging installation procedures
Shore points (bollards, piles, drilled, helical, gravity-based – Wide range in size and shape) Holding capacity dependent on the shape and dimensions, connection method and the properties of the foundation	— usually simple design and easy hook-up, but dependent on type — good access for machinery during installation allowing for accurate positioning — usually flexible with respect to horizontal angles, but dependent on type — easy access for visual inspection	— may have complex installation requirements, depending on type — may imply requirements for reinforced shore foundations — as the height of ropes are in the water level, the FPV system will have restricted access for maintenance boats — requirements from national building codes

The anchor solution shall be selected on a case-by-case basis depending on the site conditions. The following factors are of importance for selection of anchor type:

- mooring line loads, i.e. vertical and horizontal load capacity needs
- ground and soil profile constraints
- bathymetry/topology constraints
- precision requirements

- behaviour under sustained loading
- environmental impact.

Anchor type, size and installation angles are defined based on an assessment of above factors and the anchor capacity requirements provided in [6.3.2], to ensure that the combination of anchor type/size and foundation geotechnical characteristics provide sufficient holding capacity.

The theoretical capacity of the anchors shall be documented. Anchors shall be delivered with a product certificate with stated load capacity.

Anchor installation position and tolerances shall be defined in the design phase. These are verified in the post-installation survey. Guidance regarding test anchors, proof loading and post-installation survey is provided in [9.2.3].

The risk for scour around an anchor foundation shall be taken into account.

On steep slopes the need for waterbed anchors should be carefully evaluated. Gravity anchors should be avoided in steep slopes due to risk of sliding.

If bollards are used for shore moorings, requirements for bollards as per DNVGL-ST-N001 [17.10.9] and PIANC shall be considered. Regional/national requirements may apply and shall be adhered to.

For submerged gravity anchors, the capacity against uplift and sliding resistance shall be based on the submerged weight. The weight in air may be used for onshore anchors provided they are positioned above the highest water level.

One may reduce the overall number of anchor points by using shared anchors for two or more mooring lines. Caution shall be exercised, as the load pattern on each anchor would be more complex than for a single line anchor. Furthermore, one may apply clusters of anchors (and mooring lines) if higher capacity is required, e.g. in FPV system corners. However, attention shall be paid to the minimum required distance between anchors of the cluster to avoid loss of soil restraining force capacity.

The ability to inspect waterbed anchors and its accessories will be dependent on anchor type, soil conditions and any site restrictions. Embedded anchors and drag anchors will have limited accessibility for inspection during their service life. This shall be considered when establishing the O&M strategy for the mooring system. See [9.3.3] for further details regarding O&M of anchors.

In load and response analysis, the anchor points are normally defined as fixed. If relevant, dedicated software may be used for assessing the effect of anchor drag.

More details and recommendations regarding anchors may be found in DNVGL-OS-E301 Ch.2 Sec.4, edition 2018.

6.3.2 Anchor capacity

The loads to be taken by the anchors shall be calculated in a load and response assessment, see guidance in [4.5]. It shall be demonstrated that the design environment does not lead to anchor forces in excess of the holding capacity of the anchors, including a material factor. Both vertical and lateral loads on the anchors shall be considered.

The design load, T_d acting on the anchor and arising from line tension in the mooring line, which is hooked up to the anchor, shall be taken as equal to the design line tension (factored) in the mooring interface between the mooring line and the anchor.

The design criterion for anchors is expressed as:

$$R_d - T_d \geq 0 \tag{6.4}$$

Where T_d is the design load and R_d is the design anchor resistance. The anchor resistance may be expressed as:

$$R_d = \frac{R_c}{\gamma_m} \tag{6.5}$$

Where R_c is the characteristic geotechnical anchor resistance and Υ_m is a material factor.

The characteristic geotechnical anchor resistance may be taken as the mean anchor resistance as set up by the supporting soils or rock. It shall be estimated based on site-specific soil data. For additional guidance on the determination of characteristic soil properties, see DNVGL-RP-C212.

The analysis of anchor resistance shall be carried out for the ULS and the ALS. Design against the ULS is intended to ensure that the anchor with its geotechnical anchor resistance can withstand the loads arising in an intact station keeping system under extreme environmental conditions. Likewise, design against the ALS is intended to ensure that the anchor can withstand the loads arising in an intact station keeping system under accidental load conditions, or to ensure that the damaged station keeping system retains adequate capacity if one mooring line or one anchor fails.

The material factors in Table 6-6 should be applied as guidance. See DNVGL-OS-C101 Ch.2 Sec.10 [5] for material factors for different types of anchors.

Table 6-6 Anchor material factors, γ_m

Limit state	*Load factor*	*Consequence Category 1*	*Consequence Category 2*
ULS	γ_m	1.30	1.30
ALS	γ_m	1.00	1.30

Note that any regional and national requirements shall be adhered to as applicable.

The effect of cyclic loading on the soil properties shall be considered.

SECTION 7 PERMITTING AND ENVIRONMENTAL IMPACT

7.1 General

As for any power generation project, an FPV project shall obtain the relevant permits by the competent authorities.

Any relevant and applicable local, regional or national regulation shall be adhered to.

This section provides requirements, recommendations and guidance for permitting procedures and environmental impact assessment for FPV projects, which may be used as guidance in absence of or in addition to clear or relevant local, regional or national regulations.

7.2 Permits

7.2.1 General

The permitting of FPV projects follows the guidelines for ground-mounted PV to a large extent, but with several deviations following the regulations for application on/near the water. This section explains the various permit categories and to what extent existing guidelines may apply to FPV projects.

An FPV project shall obtain all the relevant and applicable mandatory permits according to national and local regulations. In case of absence of relevant and applicable permitting procedures and regulations, the recommendations in this section may be used as a guideline.

The FPV project may, depending on the situation, require the following main categories of permits:

- building permit, or equivalent, e.g. planning permission
- production and exploitation license, if applicable
- surface rights, or land and water agreements
- environmental permit, or equivalent, e.g. nature permit.

7.2.2 Building permit

The building permit (or planning permission) provides formal permission for the construction and installation, operation and decommissioning of the FPV project over its admitted lifetime. This permit shall be requested to the regional or the local competent authority and should include separate conditions for building, operating as well as for decommissioning.

It is recommended to include the following aspects in FPV projects building permits:

- Spatial policy: FPV projects can interact with zoning areas labelled as ‘water’, ‘natural shore’ and ‘waterways/traffic’, ‘public water domain’, or similar labelling, according to local or national regulations. As a consequence, use restrictions may apply, which shall be designated in the building permit. It may also be required to change the zoning label (e.g. from the label ‘public water domain’ to the label ‘industry’), in which case the authority could provide a separate zoning permit, as a part of the building permit process.
- Water or traffic authorities may have existing guidelines for installations connected to important waterways and often require a specific water permit. It is recommended to follow the existing guidelines, if any, for waterway traffic and possibly also for the maintenance requirements of the water authority. In case of the creation of a new water surface for the project, an additional water permit may also be required.
- Local authorities may already have guidelines for construction on water or for the construction of mooring docks, which may resemble existing design criteria for marinas. In this case, it is recommended to follow guidelines that apply for marinas.
- Transport impacts shall be assessed by including a road plan that includes transport emissions and the space requirements for the assembly onshore.

- Electromagnetic fields near high voltage lines shall remain within national limits for EMC levels (electromagnetic compatibility).

7.2.3 Production license

Production license may include the approval of the competent authorities (e.g. department of energy, electricity authority or spatial planning office) to produce electricity with the FPV system. National regulations may include thresholds of capacity above which projects shall apply for a production license. It is recommended, in an early stage, to assess whether the project's capacity (or any future expansions) demands a production license and henceforth to apply for such a license with the competent authority.

7.2.4 Exploitation license

Exploitation license may include the approval of the competent authorities (e.g. department of energy, electricity authority or spatial planning office) to commercially trade electricity to the grid and/or to a third party. The network operator, to whose grid the FPV project will be connected, should comment on the existence of technical conditions for connection to the network and on compliance with the applicable regulations. It is recommended, in an early stage, to request an opinion from the network operator, on the feasibility of commercial exploitation of the generated electricity.

7.2.5 Surface use rights

Surface use rights include the rights for the use of water and land surfaces by the FPV project.

Privately owned surfaces may require private sector surface agreements, e.g. a land and water lease agreement. The lease agreement shall arrange the requirements of the building permit and the environmental permit, as well as any possible use restrictions in relation to ongoing activities around the FPV project surface (e.g. quarry excavation, hydro dam operation, water treatment, recreation).

Publicly owned surfaces may require permits by public authorities that are responsible for (maintenance of) public water and land surfaces. State owned water bodies or coastal areas require permits for the use or for the construction near such water works. It is recommended to take into account any future development space, e.g. dams or dikes may be reinforced at a later stage.

Abovementioned agreements shall specify the surface rights for:

- pre-construction access rights
- construction rights
- operational rights
- cable crossing rights
- decommissioning conditions.

The land agreement shall include those cadastral land plot numbers that also include the adjacent water surface. In certain countries, the cadastral location of the FPV system is based on the location of the floating structure, whereas other countries use the anchor location on the bottom as the determinant for the location. It is recommended to align with the competent local authority to agree how they determine the FPV location.

In case that a security fence is planned to close off the entire water surface, it is recommended to secure the surface rights of the perimeter of the fence as well.

7.3 Environmental permit

7.3.1 General

An environmental permit grants permission to build, operate and decommission a system, or any other structure, while managing and mitigating environmental impact.

An environmental permit (or equivalent) may be required to obtain permission for an FPV project, depending on the project location and on identified impacts that the FPV project may have on it. Identification of these impacts is conducted through an environmental and social impact assessment (ESIA), usually performed by a project independent party. The environmental permit may include certain use restrictions and can include mitigation and/or monitoring of environmental impacts as a condition for compliance with the permit.

The preparation of an environmental permit for FPV projects may include the following:

- spatial plan: change of zoning
- environmental and social impact assessment
- landscape plan.

7.3.2 Spatial plan

The spatial plan, managed by the municipality, includes zoning interactions between the project location and surrounding objects, activities and traffic. The plan shall contain the cadastral plots and their zoning status (e.g. industry, agriculture, recreation).

If the FPV project is planned in a non-industrial location, it may require a change of zoning status in the spatial plan. If the FPV is planned in an existing industrial location (i.e. quarries, hydro lakes, reservoirs, water treatment), the FPV project may be included in or connected to an existing industrial zone.

In certain countries, a change of spatial planning zones requires that an environmental and social impact assessment is performed. In other countries, an ESIA is always required for power generation projects.

7.3.3 Environmental and social impact assessment

7.3.3.1 General

Environmental and social impact assessment should be performed by a project independent party and shall comprise the expected interactions between the FPV project and the natural environment, important habitats and species. The ESIA shall also assess the project’s social impact, including change of water/land use (e.g. drinking water, fishing, but for informal use too), physical and economical displacement, impact of cultural or archaeological values, impact on indigenous people and human rights, if any. Stakeholders and affected people shall be identified and duly considered in a social management plan with adequate consultation and surveys during the baseline studies.

ESIA shall include all mitigation and monitoring measures. If applicable, livelihood restoration plans and physical/economical displacement shall be implemented as per national and international standards.

The project ESIA shall identify the necessary mitigations, with application of a mitigation hierarchy (avoid/minimize/restore/compensate). It shall define management plans and monitoring programs for the project’s design, construction, operation, and decommissioning stages.

Guidance for environmental impact assessment (EIA) may be found in the Directive (2014/52/EU) or the US National Environmental Policy Act (NEPA) sec. 102-2c. Any ESIA requirements by local or national laws shall be adhered to. Depending on local and national regulations, it may be required to include a life cycle assessment (LCA) as part of the ESIA.

It is recommended to involve specialized ecological parties to perform an ESIA. The ESIA shall include at least a description of the location, as well as, but not limited to, the following impact considerations:

- impact on flora and fauna
- impact on habitats
- noise impact
- visual impact
- soil impact
- impact on water quality and human health.

The area of influence shall be defined for all aspects of the ESIA.

7.3.3.2 Impact on flora and fauna

A characterization of the reference situation shall be performed before start of an FPV project, including the characterization of existing flora and fauna species and the protected status thereof.

Measures shall be implemented to mitigate identified impacts on fauna and flora, when necessary:

- Any removal of nesting locations of bird species during breeding season should be avoided. These may include (temporary) construction related works e.g. sand piles.
- Solutions to re-create new nesting locations around the FPV project to stimulate avian wildlife may be considered.
- During installation and maintenance of the FPV system, no harmful anti-vegetative paints for aquatic systems should be used to control biological growth adhering to the floats.
- If a bird-repellent system is intended to be installed on or in proximity of the FPV system, with the intent of reducing soiling losses from bird droppings, see [3.4.5], its impact on the avian fauna shall be included in the ESIA. Use of specific bird-repellent systems may be restricted or prohibited by local and national regulations.
- If the water body hosts relevant fish population (e.g. fishing pond), measures shall be implemented to mitigate the impact of the FPV project on the fish population and to minimize its reduction.
- Impact assessment shall not only be focused on birds and fishes. All the important species that can be impacted such as amphibians, invertebrates, insects shall be identified in the context of the FPV project.

7.3.3.3 Impact on habitats

A characterization of the reference situation shall be performed, including the characterization of nearby important habitats.

Measures shall be implemented to mitigate impacts on habitats:

- Construction of FPV systems near important or protected habitats (e.g. mangroves, Natura-2000 areas in the EU, or equivalent) may cause species to migrate to the FPV project or away from the FPV project. If applicable, monitoring of any protected species nesting should be arranged.
- Emission values shall comply with local regulation and international standards. Emissions from construction equipment shall be limited as much as possible. This may be achieved by using only electrical equipment onsite.
- Preservation of high-stake areas, such as coastal areas, islands, atolls, reefs, and it species shall be assured.

7.3.3.4 Noise impact

Measures shall be implemented to limit noise impact:

- Noise from any cable (under water) shall not exceed applicable acoustic limits.
- Noise caused by the transformer (on the FPV or onshore) shall not exceed applicable acoustic limits.
- Noise values shall comply with local regulation and international standards.

Monitoring of compliance with acoustic limits shall be performed by a noise measurement after construction has been completed.

7.3.3.5 Visual impact

Measures should be implemented to limit visual impact:

- Visual quality of the existing landscape should be respected as much as possible.
- Flickering/glaring shall be considered as a visual impact (only regarding fixed objects, not for by-passers).
- Sight lines, from local residences onto the FPV, should be assessed.
- Colour, size and material of the FPV may be specified by the authority as a permit condition.
- Additional vegetation or fences may be considered to integrate the FPV with the visual landscape.

Such measures may be presented in a landscape plan by the developer to the competent authority.

7.3.3.6 Soil impact

The waterbed shall be inspected for soil contamination and possible archaeological value.

Measures shall be implemented to mitigate and minimize the impact on the soil of the bottom and the shores of the water body (by anchors and mooring lines):

- Mooring lines, anchors, cables or any other component landing shall not cause abrasion to fragile shorelines and shall not cause unacceptable levels of metal intrusion into the environment.
- Anchoring design and installation shall be designed to minimize impact on the waterbed or ecological values at the bottom.

7.3.3.7 Impact on water quality and human health

A characterization of the water quality reference situation shall be performed. Water quality shall be assessed as per quality standards applicable to each specific location.

The design and choice of FPV system components shall limit the impacts on water quality to an acceptable level, if applicable, to be tested and documented through water quality impact testing.

For freshwater locations, this may be achieved by using components that are verified to be used in a drinking water environment, according to relevant standards, see [5.7.2.7].

For saltwater locations, this shall be achieved by using components that are verified to withstand a salty environment without unacceptable levels of degradation, according to relevant standards.

The nature and extent of water quality changes should be evaluated using seasonally representative baseline data. Recommended parameters for data collection include, but are not limited to:

- water temperatures are various depths through the water column
- level of acidity (pH)
- dissolved oxygen
- total suspended solids
- chemical oxygen demand
- biochemical oxygen demand
- algae concentration
- chlorophyll-a.

Water quality sampling shall be performed according to relevant standards. For man-made and natural reservoirs, procedures for water quality sampling found in ISO 5667-4:2016 may be followed. For rivers and streams, sampling procedures in ISO 5667-6:2014 may be followed.

Leakage, spilling or release of unwanted substances in the water (e.g. plastics, metals, chemical additives transformer oil) shall be avoided or mitigated to acceptable levels according to local and national regulations. No heavy toxic metals shall be used in FPV system components.

Release of unwanted substances in the water body may also occur during washings of PV modules, both due to potential chemical additives for cleaning and due to the substances washed away from the PV modules into the water (e.g. bird droppings).

Guidance note:

The impact of an FPV system on the water temperature is subject of discussion within the FPV community. Numerous studies have been published on the analysis of water temperature impact. The impact varies greatly depending, among other factors, on the water coverage ratio of the FPV system in the water body, the footprint of the floating structure, the water depth, water currents and on the surrounding climatic conditions.

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7.3.4 Landscape plan

The landscape plan should visualise the envisioned FPV project environment. The landscape plan shall include mitigation strategies for impacts identified in the ESIA.

Approval by competent authorities may be required for the landscape plan (applicable as an appendix to the environmental permit). The implementation of the landscape plan may be a mandatory condition to obtain the environmental permit.

Landscape plans for FPV shall include the following aspects:

- The landscape structure should be characterized, based on morphology, hydrographic network and land occupation, delimitation of landscape units and subunits, based also on the forms of human presence and existing cultural values.
- Roads associated with the movement of machines and the presence of workers, should be included in the landscape plan.
- Any maintenance of built structures (FPV system and related infrastructure), to preserve the quality of the landscape, should be included as well.

SECTION 8 ELECTRICAL LAYOUT AND COMPONENTS

8.1 General

The electrical components of an FPV system experience different environmental conditions in comparison to ground mount PV systems. The electrical layout and all the electrical components shall comply to applicable local, national codes and international codes, standards, norms and regulations. This section contains references to applicable standards, general requirements and recommendations related to the electrical layout and electrical components of FPV systems.

8.2 Electrical layout

The electrical layout for FPV systems shall follow standard industry practice for electrical layout, with additional considerations related to the environment and characteristics of the FPV system.

The electrical components selection and electrical layout design shall be in compliance with IEC 62548, IEC 60364, IEC 61936 and IEC TS 62738 with the following additional considerations for floating PV electrical components selection and electrical layout design:

- humidity and potential water ingress into the FPV system
- increased exposure to direct sunlight
- movement of the FPV structure due to waves, currents, wind and other forces
- ease of maintenance activities
- reliability and durability of the FPV system.

The location of the inverters and other balance of system (BoS) components depends on the size of the installation and the environment. In the case of small floating installations close to the coast/land, these components may be located onshore. Alternatively, central or string inverters may be installed on specially designed floats with other BoS components. More details about the electrical system components are addressed in the following subsections.

8.3 PV modules

The PV modules used for FPV projects shall as a minimum be designed, manufactured and certified according to:

- IEC 61215 *Terrestrial photovoltaic (PV) modules – Design qualification and type approval*.
- IEC 61730 *Photovoltaic (PV) module safety qualification*.
- IEC 62804 *Test methods for the detection of potential induced degradation*.

And, where appropriate

- IEC 61701 *Salt mist corrosion testing of photovoltaic (PV) modules*.
- IEC 62716 *Ammonia corrosion testing of photovoltaic (PV) modules*.

The PV modules shall be certified by an accredited third-party testing laboratory to comply with the above-mentioned standards.

PV modules used for the project shall be supplied with a copy of IEC certification reports indicating compliance for the model numbers used and indicating the certification is in force as of the dates of PV module manufacture.

For the selection of PV modules for an FPV system, the following considerations shall be made:

- Wind load: the PV modules and the mounting structure shall withstand the maximum wind loads observed at the site. See [2.2] for considerations of wind for the project site.
- Wave loads: waves may create extra mechanical forces on a PV module, which a PV module and the mounting structure should be able to absorb without damage. See [2.3] for considerations of waves for the project site.

- Influence of salt: if an FPV system is installed in brackish or sea water the PV modules shall be certified according to IEC 61701. If framed PV modules are used, the frame shall be protected against corrosion with non-pollutant coating. The PV modules' capabilities in saline environments should be reflected in the PV module warranty.
- Chemical contaminants: if the water contains chemicals that can potentially have an adverse impact on the PV modules, this should be taken into consideration.

If the PV modules are expected to observe cyclic loads, testing according to IEC 62782 shall be considered.

The PV module junction boxes shall be compliant with IEC 62790 and have a minimum ingress protection rating of IP 67, according to IEC 60529.

Use of PV modules comprising of materials with low moisture and vapor transmission may be considered and can have a positive impact on the long-term reliability of the PV modules.

The selected PV modules should not have a negative impact on the water quality where the installation is located.

Where feasible for the project, the PV modules should be subjected to testing which approaches similar conditions as the lifetime of an FPV project.

8.4 Balance of system components

8.4.1 Inverters

Central inverters and string inverters are most used for FPV systems, in some cases micro-inverters might be considered.

For larger FPV systems, or PV systems with considerable distance to shore, it is recommended to locate the inverters, as well as the transformers, on a floating structure in proximity to the rest of the FPV array(s), with cable(s) to the onshore switching facilities and grid interconnection point. For smaller FPV systems with short distance to shore, it can be considered to locate inverters and transformers on land.

For centralised inverters, if installed within an enclosure, the enclosure shall be rated IP 44 or higher. Inverters installed on a skid platform shall be rated for outdoor use, with a rating of IP 54 or higher. Power and control electronics shall be housed in a portion of the enclosure rated IP 65 or better. All electronic circuit boards within the inverter shall be conformal coated. Central inverters, if installed within an enclosure, shall have its enclosure fitted with lightning protection via air terminal or equivalent. If inverters are housed in enclosures (containerized solution), adequate cooling system should be built into the enclosures to ensure optimal performance of the inverters.

Guidance note:

Inverter, transformer and associated switch gear may also be installed as a power conversion system(PCS) which is inclusive of the inverters, PCS transformers and PCS switchgear, but also including all connections, attachments, enclosures, software and accessories and may be housed within one or more physical enclosures and foundations..

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String inverters, if installed outdoor, shall be rated IP 65 or higher. All electronic circuit boards within the inverter shall be conformal coated.

String inverters in FPV systems may be more exposed to direct sunlight than ground mount solar installations, therefore an increase in temperature and changed humidity should be considered for the design of the enclosure. The ventilation design of the enclosure should consider the exposure to higher humidity.

The inverters shall be compliant with:

- Local grid regulations for grid connection systems.
- Grid monitoring is in accordance with the local requirements.
- IEEE 1547 *Interconnection and interoperability of distributed energy resources with associated electric power systems interfaces*.
- IEC 61000-6-2 and IEC 61000-6-4 *Electromagnetic compatibility (EMC) - Part 6-2 and Part 6-4: Generic standards – Immunity and emission standard for industrial environments*.

- IEC 62920 *Photovoltaic power generating systems - EMC requirements and test methods for power conversion equipment*.
- IEC 62477 *Safety requirements for power electronic converter systems and equipment*.
- IEC 61727 *Photovoltaic (PV) systems - Characteristics of the utility interface*.
- IEC 62109 *Safety of power converters for use in photovoltaic power systems*.
- IEC 62116 *Utility-interconnected photovoltaic inverters - Test procedure of islanding prevention measures*.

The PV inverters shall be certified by an accredited third-party testing laboratory to comply with the above-mentioned standards.

Special attention should be paid to protective materials and coatings because of their susceptibility to corrosion.

To prevent moisture penetration, it is recommended to design the cable entries at the bottom of the inverters. In case an external disconnection switch is required, this shall be located at the underside of the inverter to prevent water leakage through the door and the switch shaft.

8.4.2 Combiner boxes

Combiner boxes (AC/DC) shall comply to IEC 61439, IEC 62208, IEC 60364 and IEC 62548.

Depending on the design of the project, AC or DC combiner boxes may be used.

In both cases, due to proximity to the water body, the combiner boxes shall be suitably designed for operation in a humid environment and the ingress protection for combiner boxes installed on the floats shall be minimum IP 65.

Combiner boxes may be more exposed to direct sunlight than ground mount installations. Therefore, an increase in temperature and changes in humidity should be considered for the design of the enclosure. The ventilation design of the enclosure should also take into account the high humidity.

To prevent moisture penetration, it is recommended to design the cable entries at the bottom of the combiner boxes. In case an external disconnection switch is required, this shall be located at the underside of the combiner box to prevent water leakage through the door and the switch shaft.

8.4.3 Cabling and connectors

Photovoltaic cables (all cabling on the DC side of the inverter) shall be intended for use in PV systems and be certified according to IEC 62930. LV cables other than photovoltaic cables shall comply with IEC 60364.

All conductors between PV modules and combiner boxes shall be copper and dual insulated.

Interconnection between PV modules and combiner boxes shall only use connectors of same type with a minimum ingress protection rating of IP 68 and connect in accordance to PV module manufacturer’s recommendation.

Photovoltaic cable connectors shall be qualified as MC4 or equivalent, as defined in IEC 62852. The connectors shall be tested according to the site-specific conditions and according to IEC 60068. The connectors shall be UV resistant and minimum IP 68.

Cable trays, cable ladders, conduits and cable ties shall be UV protected. Materials used shall be designed at minimum for the lifetime of the project. Other cables exposed to direct sunlight shall be UV stabilised and shall be hydrolysis resistant.

Cable trays shall comply with IEC 61537. Cable tray systems and cable ladder systems shall be tested according to the applicable standards and codes.

Cable trays should be designed to ensure air flow through the bundle of cables installed in the cable tray. However, a solid cover to prevent from UV exposure should be considered, especially for DC and MV cable trays.

Material for cable trays may be metallic or non-metallic (such as PVC, HDPE or fiberglass) and shall for the duration of the project lifetime be suitable for outdoor installation, water resistant, corrosion resistant, nontoxic, UV resistant and resistant to weather conditions at the project location.

Submerged cable installation in water (shore supply connection) shall have water ingress protection and shall be certified and approved for the installation. If conduits are used, these shall also have sufficient water ingress protection. Medium voltage cables shall follow IEC 60183. Medium voltage cables installed directly in water shall be in compliance with DNVGL-RP-0360, DNVGL-ST-0359 and IEC 63026.

Cables used in an FPV system should be designed using appropriate correction factors and appropriate reference installation method to prevent overheating and significant energy losses.

8.4.4 Transformers

The transformer can be supplied as an independent unit or as part of an enclosed compact substation. The enclosure shall be well-ventilated and have a minimum IP rating of IP 44. In case a central inverter and a transformer are placed in the same enclosure, the enclosure and the transformer shall be well-ventilated and rated IP 44 or higher and the inverter shall be rated IP 54 or higher.

The transformer may be installed either directly on land or on float(s). In the case of installation of the transformer on a float(s), functional requirements as per [5.3.4] and performance criteria as per [5.5.4] shall be fulfilled.

Two different kinds of transformers may be used, oil type transformers and dry type transformers. When an oil-type transformer is used, a natural oil type should be applied. The risk of oil spillage or oil leaks to the water body shall be considered when selecting the transformer type, taking the site conditions into consideration. When high waves, wind and general movement of the FPV system is expected, dry-type transformers are preferred. The use of the waterbody can have implications on the choice of transformer type. If the water body is used as a drinking water source, commercial fishing or other activities where a potential oil leak can have severe effect on the activities associated with the water body, dry type transformers shall be used.

Special attention shall be paid to the oil container in order to avoid oil spills to prevent seepage into the waterbody.

Particular attention shall be given to the transformer's protective materials and coatings because of its susceptibility to corrosion.

The transformer’s mechanical design shall allow correct operation under the intended installation conditions, specifically including prolonged exposure to vibration and movement.

Transformers shall be compliant with IEC 60076.

Guidance note:

From the perspective of optimising electrical safety in an electrical installation, it is optimal to choose an IT-system because a fault current can only occur after the second insulation fault. The electrical safety is better, and availability is higher in an IT-system.

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8.4.5 High voltage and medium voltage switchgear and enclosures

Medium and high voltage component selection, medium and high voltage electrical layout design and associated enclosures shall follow standard industry practices and shall be compliant with IEC 61936. When the medium voltage equipment is installed in combination with inverters in turnkey floating solutions, these shall be in compliance with [8.4.1] and [8.4.4].

8.4.6 Earthing

Earthing and equipotential bonding shall be in compliance with local codes and standards, IEC 60364, IEC 62548, IEC 61936, IEEE 80 and follow the guidelines in IEC TS 62738.

Earthing and equipotential bonding shall be compliant to the component and equipment manufacturers guidelines, instructions and recommendations and the system earthing for the project. The earthing design shall be determined through a risk assessment where all potential fault situations are considered. The risk assessment shall also include any external influence which might have impact on the earthing system.

All exposed conductive parts shall be interconnected and shall be terminated, either to water at a suitable water depth or to the waterbody floor with earthing rods, and to the earthing of the electrical system. For specific earthing systems (such as IT systems), termination to the earthing of the electrical system may be not needed, if determined and justified by the risk assessment.

The earthing design shall always be based on the risk assessment and shall take into account the different floating technologies used. Some floating structures are made of non-conductive materials. In such cases, only if properly justified by the risk assessment, equipotential bonding and termination of the floating structures may be not needed.

The water and the exposed conductive parts of the solar installation shall not have a potential difference which can be a hazard for human or animal life. The earthing shall be designed according to the results of the risk assessment and be based on, and documented through, earth resistance measurements conducted on site.

Where functional earthing of the DC side of the installation for PID prevention is present, this shall be taken into consideration for the earthing design and in the risk assessment.

When considering terminating earthing to water or to the seabed any health and safety aspects shall be evaluated in the risk assessment. Any effects on the water quality, aquatic life and fauna shall also be considered, see Sec.7.

Guidance note:

From the perspective of optimising electrical safety in an electrical installation, it is optimal to choose an IT-system because a fault current can only occur after the second insulation fault. The electrical safety is better, and availability is higher in an IT-system

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8.4.7 Lightning protection

Lightning shall be in compliance with local codes and standards, IEC 62305, IEC 60364, IEC 61936, IEC 62548 and follow the guidelines in IEC TS 62738.

Lightning protection shall be compliant to the component and equipment manufacturers guidelines, instructions and recommendations.

When the risk analysis concludes that air terminals are necessary to protect the project from lightning strikes or it is required by local codes and standards, the rolling sphere method or other suitable methodologies shall be applied according to IEC 62305 or methodologies required by local codes and standards.

Based on the chosen methodology the number, distribution and height of the air terminals shall be determined and sufficiently documented.

The air terminals should be terminated with earth rods to the reservoir bed where possible, or at sufficient water depth.

8.4.8 SCADA

The FPV system should be equipped with a supervisory control and data acquisition (SCADA) system. All major components in the FPV system should be able to communicate with the SCADA system. The SCADA system shall follow IEC 61724.

8.4.9 CCTV and fire protection

The FPV system should be equipped with a suitable fire protection system as required by the local codes and standards or the fire risk assessment as discussed in [11.2.5]. Fire detection and fire extinguishing should be present on the FPV system, power conditioning station (PCS), O&M building, and the project substation. The design of fire protection system shall comply with the local codes and standards.

Where necessary, the FPV project should be equipped with a closed-circuit television (CCTV) system. The CCTV system shall be compliant with local codes and standards.

SECTION 9 INSTALLATION AND OPERATION AND MAINTENANCE

9.1 General

This section contains requirements, recommendations and guidance on procedures to be followed in the following phases of an FPV project:

- installation
- operation and maintenance (O&M).

For requirements, recommendations and guidance on health and safety aspects of installation and O&M, see Sec.11.

During both installation and O&M of an FPV system, guidelines and manuals provided by manufacturers shall be followed as a minimum. All installation, O&M manuals and procedures provided by the manufacturers shall be followed by trained and qualified personnel.

Adequate and exhaustive information and documentation shall be produced prior to the installation phase. In case of a change of ownership between installation and O&M phases, or at any given point during the project lifetime, all relevant information and documentation shall be handed over to the new owner.

This documentation shall include as a minimum:

- installation procedures
- O&M procedures
- description and results of the completed commissioning tests
- description of inspection criteria
- as-built design documents
- materials and components datasheets.

Prior to installation, all relevant and applicable regulations, permitting procedures, and local directives shall be adhered to.

Only qualified personnel with appropriate personal protective equipment (PPE) shall perform work on the FPV system. Involved personnel shall be properly trained in working with electrical systems, shall have adequate knowledge of the FPV system components, the FPV system design and the relevant manuals and other related documentation. Involved personnel shall adhere to and follow all relevant local codes, directives and regulations. This applies to both personnel working above water on the floating structure and to divers working in the water below and around the floating structure.

Appropriate means of access and transport of personnel and equipment on the water body should be readily available at all phases of the FPV project. The characteristics of the selected means (e.g. boat, direct walkway) should be suitable for the intended use and the foreseen installation and O&M procedures.

During both installation and O&M, special care shall be taken not to drop or lose any component, tool or material in the water. Where possible, tools should be secured to the personnel to avoid accidental dropping.

All components shall be handled with care and protected from damage prior and during installation and O&M procedures.

If storage of components is required prior and during installation and operation, a proper storage area within a controlled and protected environment should be used to avoid any damage or degradation to the packaging or components. If specific components are proven not to be subject to damage or degradation by normal environmental conditions, the storage area may be unsheltered. In all cases, the storage area should have restricted access.

If any component, prior to installation, is found to be unsuitable or not designed for the specific site condition or for the intended application, the manufacturer shall be contacted to verify and proof the suitability of the component. If that is not possible, the component shall not be used in the installation.

If any component or its packaging, prior to installation, is found to be damaged, it shall be verified and proven that the said component is still suitable for the intended use. If that is not possible, the component shall not be used in the installation.

Guidance note:

General guidance on both installation and O&M procedures for ground-mounted PV systems may be found in ASTM E3010 - 15(2019). Parts may be applicable to FPV systems as well.

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9.2 Installation

9.2.1 General

Installation of FPV systems shall follow standard industry practices, local codes, standards and norms and shall follow the equipment manufacturers' installation manuals, recommendations and instructions.

Additional FPV system installation procedures, techniques and skillsets shall be determined. These apply at least to the electrical components, the inverter/transformer platforms, the station-keeping system and the floats.

The installation manual and procedures shall include:

- technical installation procedures
- instructions and descriptions
- contingency procedures
- list of required equipment
- minimum personnel for safe installation
- applicable weather constraints
- any other constraints related to the installation of the FPV systems.

The documentation shall be made available to all involved parties of the FPV project.

Safety aspects shall always be clearly stated in procedures, instructions and/or descriptions and shall be implemented during the installation of the FPV system. See Sec.11 for health and safety considerations.

Weather restrictions applicable for the installation of FPV systems shall be defined and uncertainties in the weather forecasts shall be accounted for.

Installation of the FPV system shall be performed in accordance to the intended design specifications. If any deviation with respect to the design specifications arises during installation, this shall be properly measured, recorded and documented.

9.2.2 Electrical components

9.2.2.1 General

In this subsection requirements, recommendations and guidance applicable to installation of electrical components is provided. Installation requirements in IEC 60364, IEC 62305 and IEC TS 62738 shall be complied with.

General requirements for electrical components and layout may be found in Sec.8.

9.2.2.2 PV modules

Where possible, the PV modules should be installed at the lay-down area on land and transported to the position of the FPV system on the water body. The float manufacturer's installation manual and recommendations as well as installation manual and recommendations from the PV module manufacturer shall be complied with.

When installing the PV modules consideration shall be taken to reduce damage to the PV modules due to floating structure movement leading to potential microcracks, loading on clamps and collisions and impact on PV modules. The following shall be taken into consideration:

- Wind load: the maximum wind speed observed by the FPV system should be considered for the installation. The PV module manufacturer should be consulted for appropriate fastening of the PV modules. The installation shall be in compliance with the installation manual for the PV modules.
- Wave load: the maximum wave load observed by the FPV system should be considered for the installation. The PV module manufacturer should be consulted for appropriate fastening of the PV modules. The installation shall be in compliance with the installation manual for the PV modules.

The transport of PV modules shall be in compliance with IEC 62759.

9.2.2.3 Inverters

The manufacturer's installation manual and additional requirements for FPV systems shall be complied with. When the inverters are installed on a floating platform, the installation manual and recommendations shall be taken into consideration.

Movements of the FPV system due to waves, wind and current should be considered for the installation of the floating inverters. The manufacturer of the floating platform and inverters should be consulted to ensure that movement due to waves will not damage the inverter or reduce the inverter's performance.

After installation of the inverters, no spare parts, tools or loose objects shall be left on top or inside of the inverter enclosure. All unused terminals of the inverter shall be properly sealed and durable warning signs and labels shall be suitably fixed on the inverter.

Appropriate technique shall be ensured for transporting inverters which shall be installed on a floating platform to the location on the water body. Standard industry practices shall be followed for installation of inverters on land.

9.2.2.4 Combiner boxes

The combiner boxes shall be installed according to the manufacturer's installation manual and instructions. Additional mechanical stresses and load combinations should be considered when combiner boxes are installed on the floating structure.

Combiner boxes shall not be installed in direct sunlight. Secondary shield roofing should be established to protect the combiner boxes from direct sunlight.

The combiner boxes shall be labelled as a minimum with the following information:

- maximum voltage
- operating voltage
- operating current
- short-circuit current rating
- safety warning signages in English and the local language.

Where possible, the combiner boxes should be installed at the lay-down area on land and transported to the position of the FPV system on the water body. When the combiner boxes are installed on the floats, the float manufacturer's installation manual and recommendations as well as installation manual and recommendations from the combiner box manufacturer shall be complied with.

9.2.2.5 Cables, connectors and cable management systems

The cables shall be installed according to the cable manufacturer's installation manual and/or instructions.

Photovoltaic cables and AC-cables should be laid out-of-water, mechanically protected (where necessary), and protected against UV. The cables shall be secured to minimize any unintended contact with water. Where applicable, cables shall be laid in cable trays, on cable ladders and/or in conduits.

If the cables are designed to be submerged in water for the lifetime of the project, or are submarine cables, these may be installed in water. Such cables shall be installed according to the cable manufacturers installation manual, instructions and/or recommendations.

The appropriate cabling route should take into consideration cable losses as described in [3.7.3] and [3.7.4].

If conduits are used in the cable installations, they shall be installed so that there is no water accumulation inside the conduit.

Cables, cable ladders, conduits and/or cable trays should be laid to minimize biofouling.

Certain parts of an FPV system are generally subject to movement due to waves, current and wind. The installation of cables between such parts shall accommodate for this movement. To prevent failure of cable terminations or damage as a result of mechanical stress, a mechanical tension release and/or additional cable length should be implemented. Cables from the floating array to shore shall have sufficient length and flexibility to accommodate all movements of the floating construction (changes in water level, horizontal movement, due to heavy winds and waves or other influence) with sufficient slack to prevent mechanical damage. Contact between cables and sharp edges within the structure shall be avoided.

The materials used for the cable installation, such as bolts/nuts/washers and others shall be compatible with the material of the cable conductor and suited for the environment. Thicker anti-corrosion coating should be considered for the installation as the connectors will be exposed to a humid environment, and will at times be in contact with water.

Cables shall be accessible for maintenance, inspection and repair and cables shall be protected against scraping and cutting at sharp edges. A suitable edge casting profile may be used.

Connection of cables on water shall be avoided as much as possible to prevent risk of moisture ingress. It is recommended to connect the majority of cables on shore before transferring the system onto the water.

9.2.2.6 Transformers

The manufacturer's installation manual and any additional requirements for FPV provided by the manufacturer shall be complied with.

When the FPV system experiences movement due waves, wind and current, this should be carefully considered for floating transformers. The manufacturer of the floating platform and transformers should be consulted to ensure that movement due to waves will not damage the transformer or reduce the transformers' performance.

Depending on the selection of transformers, as outlined in [8.4.4], appropriate measures shall be taken during installation to mitigate the risk of potential oil leaks from oil type transformers.

After installation of the transformers, no spare parts, tools or loose objects shall be left on top or inside of the transformer enclosure. All unused terminals of the transformer shall be properly sealed, and durable warning signs & labels shall be suitably fixed on the transformer.

Appropriate technique shall be ensured for transporting transformers which shall be installed on a floating platform to the location on the water body. Standard industry practices shall be followed for installation of transformers on land.

9.2.2.7 Earthing and lightning protection

The earthing and lightning protection shall be installed according to the manufacturer's installation manual/instructions.

The air terminals will be subjected to mechanical stress due to movement of the FPV system, which should be considered in the installation. The air terminals shall have sufficient distance to the FPV system to avoid flashovers to exposed conductive parts of the FPV system.

Testing the earthing and lightning system shall follow standard industry practices and local standards and codes.

9.2.2.8 Other electrical components

Installation of other components shall follow the installation manual from the manufacturers, floating technology providers and standard industry practices.

In general, the installation procedures shall take into account:

- humidity and potential water ingress into the FPV system
- increased exposure to direct sunlight and temperature increase
- movement observed due to waves, currents, wind and other forces.

9.2.2.9 Commissioning, capacity and performance test

Commissioning, capacity and performance tests shall follow standard industry practices for testing of PV systems.

The overall inspection and tests for the FPV system shall follow IEC 62446-1 and shall include the following:

- inspection, testing, start-up, operating tests and acceptance of the electrical systems and sub-systems
- inspection, testing, start-up and operation testing of the plant, related equipment and systems
- inspection, testing, start-up and operating tests of plant auxiliary equipment
- acceptance tests.

Factory acceptance test (FAT), site acceptance tests (SAT) and site integration tests (SIT) shall be conducted and observed where applicable.

Commissioning tests shall be conducted according to IEC 62446 and/or as per the requirement specified in the local standards for commissioning of the FPV system.

Capacity test and long-term performance test shall be conducted according to IEC 61724.

The FPV system shall be subjected to thermography according to IEC 62446-3.

9.2.3 Anchoring and mooring

In this subsection, requirements, recommendations and guidance applicable for installation of mooring systems and its anchors is provided.

General component and design requirements applicable to anchoring and mooring systems may be found in Sec.6.

The complete station-keeping installation phase shall be thoroughly planned and documented in the installation procedures.

Weather restrictions applicable for the installation of the anchors and mooring system should be defined and uncertainties in the weather forecasts should be accounted for. During the installation phase it may be necessary to use a temporary or intermediate mooring system for a short period of time before the final mooring arrangement is hooked up. The temporary mooring system and all its components shall normally be designed as per requirements for weather restricted operations if the criteria for such operations are met. See DNVGL-ST-N001 [2.6] for further guidance.

All mooring line components shall be carefully controlled during transport, storage, handling and installation to ensure that the capacity of the mooring lines is not compromised.

Moorings shall be laid out to have sufficient clearance with any waterbed structures or obstacles during installation.

Special care shall be taken to avoid twisting of chain links, fibre ropes and steel wire ropes during installation. Twisting may significantly impair the resistance to ultimate and fatigue loads.

The selected anchor installation method shall reflect the requirements to accuracy, which may be influenced by bathymetry, seabed obstacles and the structure’s sensitivity to tension variations. For embedded anchors the installation angle (relative to horizontal plane) should be sufficiently large to avoid deflection in transition to harder soil layers. An installation angle in excess of 50 degrees is therefore recommended. After installation, it shall be documented that the target installation depths are achieved.

Specific installation and testing procedures and other important considerations regarding anchor installation is highly dependent on anchor type and ground/soil conditions. Detailed procedures shall therefore follow the anchor manufacturer manuals and instructions and/or applicable design standards specifically made for the selected anchor types. Installation of test anchors prior to installing the final anchors is recommended to verify the geotechnical load capacity assumed in the design phase. If lower capacities than assumed are achieved, mitigating actions, e.g. in terms of increasing the number of anchor points, shall be implemented.

The risk of anchor failure is reduced by proper post-installation testing. Anchors shall therefore be proof load tested after installation and test records shall be kept. Requirements to proof loading are dependent on anchor type and shall be provided in the anchor manufacturer manuals. Uncertainties in the estimated anchor loads and the consequences of anchor displacement should be considered when defining the test loads. Larger uncertainties should imply higher test loads. For embedded anchors, it is recommended to test to a load corresponding to the maximum load at the anchors in the ULS analyses sustained for 15 minutes.

A proper post-installation survey shall be carried out for the mooring system and anchors. The as-installed station-keeping system shall be documented, including line angles, anchor positions and line pretension values. The findings from the post-installation survey shall be compared to the defined tolerances assumed in design. If the as-installed system is outside the defined tolerances, additional analyses shall be carried out to document the effect. The post-installation survey will serve as a valuable baseline for subsequent inspections during the service life of the installation.

9.2.4 Floats

In this subsection, requirements, recommendations and guidance applicable for installation of floats and floating structures is provided.

General component and design requirements applicable to floats and floating structures may be found in Sec.5.

The installed layout of floats shall allow for sufficient spacing between individual sections and parts of the system, in order to avoid all contact as caused by the natural movement and flexing of the floating structure.

PV modules should be installed over a fire-retardant or fire-resistant mounting structure, with space in between that allows sufficient circulation of air beneath them, unless practically impossible due to the design (eg. for membrane floats)

All the floating components shall be carefully transported, stored, handled and installed to ensure that the structural integrity of the floating platform is not compromised. Adequate and appropriate storage infrastructure (indoor or outdoor) for safety and identification of floating structure should be arranged.

If the floating system is assembled directly on the water body, the laydown area for assembly of the floating platform shall be free of obstacles and sharp surfaces, which could damage the floats. Adequately sized assembly area shall be made available for the floats, depending on the size of the FPV system and the installation procedures outlined in the manufacturer manuals.

A suitable launching area may ease deployment efforts and reduce damages during assembly and interconnection works. The preparation and construction of launching areas, while conforming to environmental permits, should take in consideration site-specific parameters like bank's natural slope for suitable angles of entry, water variations and additional site-specific recommendations from manufacturers on deployment methods. In case the assembly of the floating structures is not implemented directly on the water body, this important infrastructure onsite enables workers or lifting machinery to launch the structures into the water body safely, with minimal effort and without compromising the structural integrity of the FPV array and/or floating structure, including the interconnections between floats.

Assembly and interconnection of floating structures shall comply with installation manuals of manufacturers. Completion tests, prior to towing the structure to its designated operational position, shall include visual checks of the overall structure with any additional functional tests on the integrity of the structure in accordance to manufacturer's requirements.

The following functional tests, and any additional relevant test, shall be considered prior to commissioning of the FPV system:

- Function under expected maintenance load: the floats in the floating structure shall function as required, see [5.3] and [5.5], following the introduction of expected maintenance loads.
- Short integrity test: the structural integrity of the floating structure should be tested in the environment expected during operation for a period of 5 -10 days. Minimum environmental conditions may be specified for a given FPV system. Survey of interconnections and stress points in the floating structure shall be well documented.

9.3 Operation and maintenance

9.3.1 General

General solar PV maintenance practices and procedures from IEC 62446-2 shall be followed.

Additional FPV O&M procedures, techniques and skillsets shall be determined to ensure operational reliability, longevity, security, and efficiency. These comprise at least the electrical components, the station keeping system and the floating structures.

Safety aspects shall always be clearly included in O&M plans and manuals and shall be enforced and respected by personnel working on and in proximity of the FPV system. See Sec.11 for health and safety considerations.

Weather restrictions applicable for the O&M of FPV systems should be defined and uncertainties in the weather forecasts should be accounted for.

Monitoring practices shall be done according to IEC 61724-1.

An adequate amount of spare parts shall be maintained, and stock should be kept up to date, complemented and documented.

Preventive maintenance procedures shall be clearly identified and included in the O&M plans and manuals.

Corrective maintenance procedures shall be clearly identified and included in the O&M plans and manuals, covering the failure scenarios identified through a risk assessment and not sufficiently mitigated through design and preventive maintenance.

It is recommended to include in the O&M plans and manuals and to implement predictive maintenance procedures as well. Predictive maintenance is useful to predict in a timely manner and potentially avoid upcoming failures.

Appropriate means of access to the floating structure and its components should be readily available on-site or in close proximity to the site, to avoid delays in planned and un-planned O&M procedures. The characteristics of the selected means (e.g. boat, direct walkway) should be suitable for the intended use and the foreseen installation and O&M procedures.

9.3.2 Electrical components

9.3.2.1 General

The operation and maintenance of the electrical part of the FPV system shall follow standard industry practices and EN 50110, or an equivalent national standard, and IEC 62446-2.

9.3.2.2 PV modules

The PV modules shall be inspected and undergo maintenance procedures according to IEC 62446-2 and according to the PV module manufacturers maintenance manual. In general, inspections shall be conducted when performance abnormalities are detected through the SCADA or monitoring system.

Infrared thermal inspections shall be conducted according to IEC 62446-3 on an appropriate interval and after severe weather events where damage to PV modules are suspected.

Electroluminescence (EL) inspections shall be performed when serious defects like potential induced degradation (PID) are suspected. The inspection procedure may be performed manually or using drones. It is recommended to perform periodic EL batch testing of PV modules: each batch shall include sample PV modules from identified higher stress areas.

The cleaning schedule of the PV modules should be adequate to the environmental conditions and should be done after expected periods of high soiling or fouling. With sufficient operational experience data from the project, preventive cleaning maintenance should be considered. The cleaning procedure may be performed manually or using cleaning robots.

High degrees of soiling by bird droppings have been observed at FPV projects. Measures may be applied to reduce the presence of and soiling by birds on the FPV system in accordance with environmental considerations in [7.3.3.2].

In events of PV module failure or irreversible under performance which leads to PV module replacement, the maintenance manual from the floating PV technology manufacturer shall be followed when conducting PV module replacement.

Guidance note:

When conducting PV module cleaning, the water in the water body may be used. It is however recommended to control that the water quality will not have negative impact on PV module performance or lifetime. Choice for use of the water for cleaning and use of chemical during cleaning may be consulted with the relevant environmental authority and/or owner of water body.

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9.3.2.3 Inverters

The inverters shall be inspected and undergo maintenance procedures according to IEC 62446-2 and according to the inverter manufacturers maintenance manual. In general, inspections shall be conducted when performance abnormalities are detected through the SCADA or monitoring system.

Standard industry practices shall be followed when conducting inverter maintenance.

Inspection of inverters for potential damages shall be conducted after severe weather events. The float technology maintenance manual and the inverter manufacturers maintenance manual, instructions and/or recommendations shall be consulted to determine when inspections should be conducted after weather events.

In events of inverter failure or irreversible under performance which leads to inverter replacement, the maintenance manual from the inverter manufacturer and the instructions from the floating platform and/or floating technology provider shall be followed when conducting the replacement.

Maintenance work for inverters and replacement of components in the inverter should be performed by the manufacturers service personnel, or personnel with appropriate training.

9.3.2.4 Cables and connectors

Cables and connectors shall be inspected and undergo maintenance procedures according to requirements in IEC 60364 and IEC 62446-2 and according to the cable and connector manufacturers maintenance manuals. In general, inspections shall be conducted when performance abnormalities are detected through the Scada/monitoring system.

Special attention should be paid to cables and connectors which are unintentionally in the water. The cables should be removed, cleaned, rerouted and fastened to their original design position, or replaced if necessary. Connectors should be replaced following instructions of the connector manufacturers.

The potential wear and tear of cables due to movement of the floating structure and its components shall be properly monitored and periodically controlled.

Particular attention should be given to areas where there is potential for insulation faults. If insulation faults are detected or there is visible damage to the cable sheath, the cables shall be replaced, the root cause of the damage shall be found and be remedied.

Strain on cables and connectors or visible degradation shall be remedied, and components which have been subject to degradation and strain should be replaced.

Marine growth on submerged cables should be properly monitored, the weight of material attached to the cables should be periodically assessed and an adequate cleaning schedule for removal of said material should be planned.

Degradation and loose cable management system shall be remedied and replaced if necessary. Replacement should be done if there is potential for failure of the cable management system damaging cables.

9.3.2.5 Transformers

The transformers shall be inspected and undergo maintenance procedures according to the transformer manufacturers maintenance manual. In general, inspections shall be conducted when performance abnormalities are detected through the SCADA or monitoring system.

Standard industry practices shall be followed when conducting inverter maintenance.

Inspection of transformers for potential damages shall be conducted after severe weather events. The float technology maintenance manual and the transformer maintenance manual, instructions and/or recommendations shall be consulted to determine when inspections should be conducted after weather events.

In events of transformer failure or irreversible under performance which leads to transformer replacement, the maintenance manual from the transformer manufacturer and the instructions from the floating platform and/or floating technology provider shall be followed when conducting the replacement.

Maintenance work for transformers and replacement of components in the transformer should be performed by the manufacturers service personnel, or personnel with appropriate training.

9.3.2.6 Other electrical components

Operation and maintenance procedures for other electrical components shall follow IEC62446-2 and the manufacturers maintenance manual.

Standard industry practices shall be followed when conducting maintenance.

Inspection of electrical components for potential damages shall be conducted after severe weather events. The electrical components maintenance manual instructions, and/or recommendations shall be consulted to determine when inspections should be conducted after weather events.

In events of component failure, the maintenance manual from the manufacturer shall be followed when conducting replacements.

Special attention should be given to water ingress and humidity inside enclosures, as well as corrosion and UV damage. When there is visible damage to the components which may lead to failure, the components shall be replaced. If there is visible humidity in enclosures, this shall be remedied.

9.3.3 Anchoring and mooring

An O&M plan for the anchoring and mooring shall be established and cover strategies for inspections, maintenance and spares. The plans shall be based on a risk assessment, so that emphasis on high-risk items is ensured. Both the anchoring and mooring design and the findings from the post-installation survey shall be input to the risk assessment so that any deviations from original design are accounted for. The plans shall include justification of the nature, the reason, the procedures and the periodicity of the activities that shall be performed. Specific inspection and maintenance needs applicable for the different types of mooring line materials included in the FPV system shall be reflected in the plans.

The anchoring and mooring system should be inspected for wear, fatigue, corrosion, chafing, severe marine growth, bio-fouling and other forms of degradation or damage by means of visual inspections performed by divers or remotely operated vehicles (ROV). The connection points between the float and the mooring line shall be included in the inspection. For rope segments, the length shall be measured to document any permanent elongation (creep).

The frequency and scope of inspections shall be justified based on a risk assessment and documented in the O&M plans. It is recommended to increase the inspection frequency in critical areas of the system and in areas with previously recorded damages or flaws. Special events such as storms shall trigger inspections. It is recommended to alternate the inspection scope between visual inspections requiring less effort and more in-depth inspections involving records of marine growth and additional associated weight and detailed measurements of mooring line components to detect any wear. Cleaning of marine growth would normally be required to obtain detailed measurements. For chains, the same chain link should ideally be measured in subsequent inspections. Sampling of mooring components for detailed assessment and testing may be considered.

Guidance note 1:

Sampling of mooring components for detailed assessment and testing is a useful method to gain insight regarding the effect of loading on the line and site-specific degradation of the mooring components due to external factors such as UV, temperature, growth, soil contact. The sample lines may be picked from a critical part of the mooring system, i.e. lines that have been exposed to the largest loads. Strength and stiffness properties of the used components may be established from testing. For ropes, it is recommended to have a test facility which allow for testing of the full length of the rope segment. Alternatively, the rope may be cut into shorter part or only subropes may be tested. Stiffness and strength values obtained from testing may be compared to the values assumed in design to check if conservative assumptions have been made. The findings are fed back into the O&M plans. If degradation is found to be more severe than anticipated, actions in terms of more frequent or replacement of critical mooring components may be considered.

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The integrity of the mooring lines shall be monitored. Corrective measures in terms of replacing failed lines shall be carried out as soon as practical possible after a line failure is detected. Sensors (e.g. strain gauges) may provide continuous integrity monitoring. Large deviations in position measurements (e.g. GPS sensors) may also indicate a line failure, but will only work for systems with few lines where a line failure will influence the motions. An alternative measure for monitoring the integrity of mooring lines is to increase the frequency of diver inspections. This method provides non-continuous integrity monitoring, implying that a line failure is not detected immediately.

It is recommended to regularly measure the tension in the mooring lines. Findings from tension measurements may trigger preventive maintenance, e.g. to adjust lines in case of uneven tension distributions. Strategies for monitoring mooring line tension shall be defined in the O&M plans.

Line tension sensor measurements may provide useful and continuous insight regarding the mooring system performance and any flaws (e.g. uneven tension distributions) may be detected. Alternatively, the mooring line tension may be derived from measurements of the top angle of the mooring line. The measurements may be carried out as a part of the regular inspection campaigns. Corresponding water level should always be recorded. Weak links with a known breaking strength lower than the other mooring line components may be used as a method to detect when the mooring system has been exposed to a larger load than a threshold value corresponding to the strength of the weak link.

Guidance note 2:

The need for installing sensors for tension measurements may be carefully evaluated. For systems with many mooring lines it is impractical and costly to install and monitor data for all mooring lines. Sensors on selected critical lines in the system may be considered. Furthermore, caution should be exercised when interpreting the sensor data as the values may drift over time or the sensors may fall out completely. Tension measurements may also be applied to verify the calculations performed in the design phase. For the purpose of verifying design assumptions, it would also be recommended to have measurements of wind, waves and position data.

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Anchor inspections shall be conducted regularly and be included in the O&M plans. The scope shall as a minimum include visual inspections to detect any wear or other degradation on the anchor or anchor pad eye.

For gravity and drag anchors, inspections shall verify the position (vertical and longitudinal) of anchors and identify any displacement which may have occurred during operation. Corrective actions, such as re-installing or replacing the anchor, shall be promptly executed if anchor displacement is detected. An automated GPS positioning system may be implemented to monitor the position of anchors without need of inspections.

9.3.4 Floats

Floats shall be periodically inspected for wear, fatigue, loss of buoyancy and other forms of degradation or damage by means of sensors and visual inspections. Inspections shall also be carried out to identify the potential damages listed below following extreme weather events, collisions or stranding of the FPV system. Maintenance shall be done according to inspection outcomes and manufacturer’s manuals.

Inspections should be aimed at identifying the following potential damages, including but not limited to:

- Puncture: visual inspection of portion of floats which are not submerged shall be carried out to identify any puncture points. Depending on the risk assessment, inspection of submerged portion of floats may be required (i.e. for floats with transformers).
- Cracks: visual inspection of portion of floats which are not submerged and connection points shall be carried out. Inspection should focus on areas which are considered to be more susceptible to cracking (e.g. areas around connection points).
- Loss of buoyancy/stability: visual inspection of the floats to assess alignment of floats relative to floats in an FPV system shall be carried out. For individual floats or floating rafts an inclinometer may be used to assess loss of stability.
- Loosening of connection pins, if present: visual inspection of the interconnections of the floats and floating rafts shall be carried out. If applicable, sample of the joints shall be torque tested in line with manufacturer’s requirements. If applicable, fasteners shall be checked against torque marks.

- Loss of components: the joints, platform or structure attaching components to the floats and float interconnections shall be inspected for signs of degradation, failure or loss of fasteners and/or pins.
- Corrosion of metallic components: all metallic components and connections shall be inspected for corrosion. Particular focus should be on components linked to critical failure e.g. inverter and transformer housing.

Marine growth on the floating structure should be properly monitored, the weight of material attached to the floating structure should be periodically assessed and an adequate cleaning schedule for removal of said material should be planned.

Maintenance works may require single or multiple floats to be temporarily removed from the FPV system to undergo repair or replacement. In such instances the removal of the floats shall not compromise the functional requirements and performance criteria, as stated in [5.3] and [5.5], of the remaining floats in the FPV system, for the period of maintenance works. If the functional requirements and performance criteria cannot be met during the time of repair or replacement, then additional mitigation measures and temporary solutions should be considered.

SECTION 10 DECOMMISSIONING

10.1 General

This section provides requirements, recommendation and guidance for decommissioning of FPV systems.

10.2 Decommissioning

The decommissioning phase occurs at the end of the system's service life, either with the intent of re-qualifying or re-using parts of the system, or to permanently withdrawing it from service and removing it, see Figure 10-1.

A decommissioning and deconstruction conceptual plan shall be developed and documented before construction of the FPV system. Decommissioning can occur after the intended service life or as a consequence of premature failures or damages which prevent the FPV system to be operating as intended.

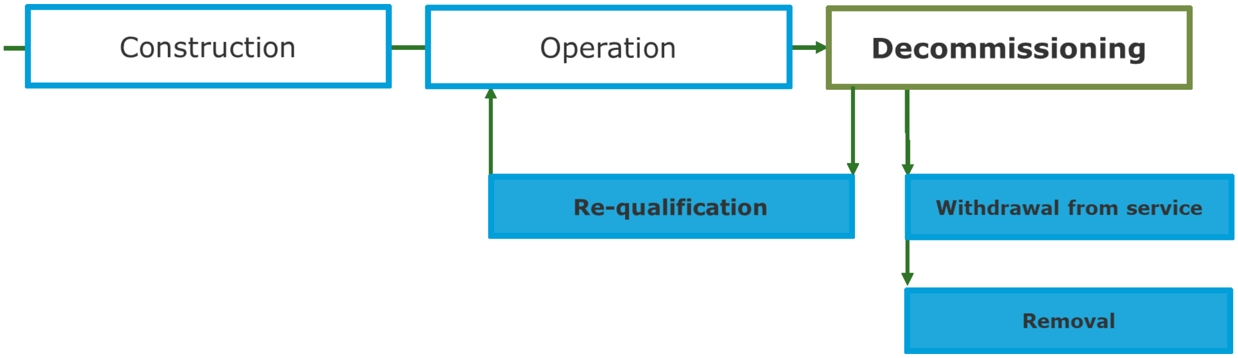

Figure 10-1 Decommissioning phase within the project life cycle

Decommissioning is the set of activities associated with taking the system out of service. Depending on applicable legislation, out-of-service systems, or elements thereof, the system may be abandoned (requiring future management) or removed.

A time schedule for each step and activity, taking into consideration weather constraints and seasonal weather conditions, should be included. Decommissioning plans may be a requirement for compliance with building permits, environmental permits or other permits in accordance with local, national and international regulations.

Decommissioning procedures for specific components included in the decommissioning plan shall be in accordance with instructions from the components' manufacturers.

For decommissioning of power cables, DNVGL-RP-0360 Sec.8 may be used as a reference.

Decommissioning plans may be updated during the installation and O&M phases of an FPV project, in case of changes in assumptions, conditions or applicable regulations. Any change shall be justified, documented and in accordance with local, national and international regulations.

The decommissioning plan shall be developed on the basis of a risk assessment considering safety and environmental risks which might occur during the decommissioning activities. Potential risks identified within the risk assessment shall be properly documented and mitigated. See Sec.7 for environmental impact assessment and Sec.11 for safety considerations. Depending on the safety and environmental risks identified and on the type of FPV system, local authorities should be consulted and informed about the decommissioning activities.

The impact of the decommissioning phase on the environment should be minimized and the project site should be returned as close as reasonably possible to the conditions prior to the installation of the FPV system, unless otherwise planned, documented and agreed in the relevant permits and plans.

The following potential impacts on the environment for the decommissioning phase should be taken into consideration, including but not limited to:

- disturbances to fauna in and around the water body
- impact on local aquatic and non-aquatic flora
- impact on water quality and water composition
- potential release of pollutants in the water body during decommissioning
- permanent modifications of bathymetry and physical characteristics of the water body
- emissions related to decommissioning activities
- emissions related to transport, disposal and recycling of scrap components and materials.

The impact of decommissioning activities on other commercial and recreational activities in and around the water body shall be assessed, including but not limited to:

- temporary and/or permanent obstruction for surface navigation and access to the water body
- disturbances to planned and unplanned commercial activities
- interference with normal operation of neighbouring infrastructure (e.g. hydro dam operation, water treatment)
- potential induced risks to by-passers and personnel involved in neighbouring activities.

The decommissioning plan shall include instructions for future management of scrap components and residual materials from the FPV system, including both hazardous and non-hazardous material. It is recommended to maximize recycling of materials and components, when possible. Any non-recycled material shall be correctly disposed according to local, national and international requirements.

In case the decommissioning plan includes parts of the FPV system being withdrawn from service, but not removed, this shall be properly documented and managed in accordance with local, national and international regulations. In addition, any unretainable component or tool lost underwater during decommissioning phase shall be recorded and documented.

SECTION 11 HEALTH AND SAFETY

11.1 General

Health, safety and environment (HSE) risks in FPV projects shall be identified and managed with the following documents:

- HSE risk assessment
- HSE management plan
- fire safety plan
- lift plan.

An HSE risk assessment shall be performed and documented to identify risks, including specific conditions of the FPV project, which depend on the project location and on the FPV system design choices and characteristics.

An HSE management plan shall be implemented to ensure compliance with international, national and local health and safety regulations, in the context of the location and design of the FPV.

Local HSE authorities (e.g. fire brigade, worker safety authorities) shall be proactively involved and their approval of HSE risk management plans shall be acquired.

Guidance on the environment risks can be found in [7.3.3], while this section focuses on health and safety

11.2 HSE risk assessment

11.2.1 General

The project HSE risk assessment shall contain as a minimum the items mentioned in the following sections and appropriate mitigation measures. Identified HSE risks and mitigation measures shall be documented and consolidated into the HSE management plan, which shall include the fire safety plan and the lift plan. The HSE management plan shall be presented for approval to the local worker safety authority and it shall be implemented by the EPC party.

HSE risk assessments shall be conducted using appropriate methodologies such as failure mode and effects analysis (FMEA), bowtie analysis, or equivalent alternatives. Complementary processes which may be used to implement the HSE risk assessment include hazard and operability study (HAZOP) and hazard identification (HAZID).

For guidance on FMEA, see IEC 60812.

For guidance on HAZOP, see IEC 61882.

For guidance on HAZID, see ISO 17776.

Guidance on risk mitigation measures may be applied as per EU Directive 2016/425 or OSHA Standard 1926 on personal protective equipment.

11.2.2 Risk environment

The main worker safety risk factors for FPV projects are water, waves and wind.

Table 11-1 below summarizes the normal working conditions, in terms of wind speeds and wave heights, that are typically associated with different risk environment categories, according to the EC Directive 94/25/EC.

Table 11-1 Risk categories and associated wind force and wave height

Risk category	*Wind force [Beaufort]*	*Wind speed [m/s]*	*Wave height [m]*
A – Ocean	> 8	> 17-20	> 4

Risk category	*Wind force [Beaufort]*	*Wind speed [m/s]*	*Wave height [m]*
B – Offshore	≤ 8	≤ 17-20	≤ 4
C – Inshore	≤ 6	≤ 11-13.5	≤ 2
D – Sheltered waters	≤ 4	≤ 5.5-8	≤ 0.5

Within the scope of this RP, risk categories C and D are considered relevant. These categories should be used to determine the expected environmental circumstances, for which the worker safety provisions apply, as per national HSE requirements.

11.2.3 General health and safety recommendations

When working near, in or on water, workers shall never work alone. Life vests shall be always worn. In case operations by divers are expected, divers shall be properly trained and certified professionals. Other personnel should have a swimming diploma and lifebuoys should be strategically positioned throughout the FPV array.

Risk of drowning and injury shall be mitigated by sufficiently present supervision by trained personnel, at least licensed for first aid, mouth-to-mouth and cardiopulmonary resuscitation (CPR).

Communication systems within the floating platform and from the floating platform to shore shall always be available.

A shelter location, appropriate for the project location, should be present in proximity of the floating platform.

In case of wind speeds ≥ 17 m/s, or in case of lightning, any kind of installation work, inspection or maintenance on the FPV system shall be avoided.

In case of snow, ice, or low temperatures (<5°C or <41°F), workers shall remove snow/ice first from the FPV system, before safe working can be guaranteed. Blankets or heating equipment should be present in proximity of the FPV system.

Risk of hyperthermia while diving (>36°C or >97°F) should be mitigated by providing ample hydration to workers (divers) and avoiding caffeinated liquids and hot meals. It is recommended to wear wetsuits only when diving. A shaded shelter should be provided if the FPV system location is expected to present high ambient temperatures.

11.2.4 Installation, operation and maintenance activities

In addition to the general HSE recommendations, the following recommendations shall be followed during the installation and O&M of the FPV system. For detailed requirements on installation and O&M procedures, see Sec.9.

Risk of injury (i.e. from crane activity) shall be mitigated by performing assembly and installation only by trained personnel and by following site-specific installation and O&M plans.

Workers or visitors shall wear personal protection equipment (PPE), including a life vest, whenever in proximity of the water body or on the water body.

Risk of crushing or drowning due to (defective) boats or accidents shall be mitigated by periodic controls of the status of the boats after placing them into the water. Boats shall be manoeuvred at safe speed.

Risk of injury due to sharp edges and rough surfaces can be limited by having adequate first aid equipment and first aid-trained personnel shall be always present on-site during work, in order to promptly react to mitigate injuries due to sharp edges and rough surfaces.

11.2.5 Fire safety

A fire safety risk assessment shall be performed, properly documented and used to identify appropriate mitigation measures.

In FPV projects, a fire risk assessment shall account for the presence of flammable system components, moving parts, varying mechanical loads and changing weather conditions that affect both the risk of fire and the effectivity of extinguishing operations.

Tests as per [5.7.2.6] shall be carried out to assess the flammability of the floats. If required as per the fire safety risk assessment, flame retardant additives should be considered.

Risk of fire caused by electrical failures shall be inherently minimized by complying to the electrical requirements in Sec.8.

Formal approval shall proactively be sought with the relevant local and national authorities (among others the fire brigade) on the fire safety plans. Fire safety plans shall include the following, but not limited to:

— evacuation walkways (on shore and on the floating structure, including signs)
— moving space for a stretcher and the identification of a shelter location
— spark prevention measures (including no smoking policy)
— identification of blast perimeters of transformers, combiner boxes and inverters
— identification of components made from fire retardant materials
— locations of fire extinguishers and fire hydrants (including signs)
— testing regimes for fire extinguishers and fire hydrants
— designated muster stations
— access scenarios for fire brigade (including the consideration of required platform buoyancy).

It is recommended to consolidate abovementioned risk aspects into a fire safety certificate, or equivalent, that may be issued for the project by the local fire safety authority. Formal approval shall proactively be sought with the relevant local and national authorities (among others the fire brigade) on the fire safety plans.

11.2.6 Heavy lifting

Risks pertaining to heavy lifting shall be properly assessed and mitigated. Lifting risks and mitigation measures shall be included into a project lift plan.

Adequate stability of any workspace on the floating structure should be provided.

The workspace shall be safe to carry heavy equipment and provide enough buoyancy to account for additional personnel and equipment.

It is recommended to apply EC Directive 90/269/EEC (EU-OSHA) on manual handling of loads where there is a risk of injury to workers. Risk of musculo-skeletal injury shall be mitigated by complying with local HSE regulations for maximum load lifting. Prior to any lifting, appropriate lifting plans and lifting instructions shall be provided. Except for small tools, manual lifting of equipment should always be performed by a minimum of two workers. Appropriate organizational measures shall be taken to ensure that workers and/or their representatives receive general indications and, where possible, precise information on the weight of a load and on the centre of gravity of the heaviest side when a package is eccentrically loaded. It shall be ensured that workers receive proper training and information on how to handle loads correctly and the risks they might be exposed to.

11.2.7 Walkways

The floats with function of walkways shall provide enough width to allow workers to move without difficulty. Workers shall be provided with enough space to carry equipment and parts to and from their workspace.

A clear indication with physical markers (eg. stickers) should be used to distinguish walkways from fragile elements, in order to prevent workers from seeting foot on fragile elements of the system. The walkways shall have adequate anti-slip surfaces. It is recommended to avoid cavities within or in close proximity of the walkways in order to prevent stumbling or accidental falls.

It is recommended to design ample space for (dis)embarkment on the FPV array. The landing platform, or its equivalent, should be at least 2 m in length, as required in INDS28.

11.2.8 Working in water

11.2.8.1 Water quality

Certain environments pose additional risks for worker safety due to the quality of the water in which workers may be active. Examples of such environments are (among others) a water treatment plant or a water sewage plant.

It is recommended to determine the water quality level of the workspace by application of testing procedures described in ISO/TC 147/SC 6 and to apply national standards on water quality in line with maximum allowable concentration of harmful substances in the water.

Disinfectants and a shower should be available onsite, in case workers are exposed to unsafe water quality. Exposure to unsafe water quality shall be limited as much as possible and its effects should be mitigated(e.g. by equipping workers with protective dry suits).

11.2.8.2 Diving

The installation and O&M procedures of an FPV system may require the use of divers. Examples of such activities may be, but are not limited to, the arrangement of anchors or submerged mooring lines, or cleaning of below-water components.

There are inherent dangers associated with all diving activities. Factors that should be considered when assessing diving operations at an FPV project site comprise, but are not limited to:

- the site’s altitude relative to sea level (determining decompression times)
- water temperature
- water quality
- the presence of obstacles that could impair movements or create impediment to lifelines, air supply umbilicals or communication cables
- size and footprint of the floating structure, in particular concerning available uncovered locations within the floating structure perimeter for a diver to resurface.

The internationally accepted practice is for air diving to take place up to a maximum of 50 m and thereafter mixed gas should be used.

When planning diving operations on an FPV project site, a full risk assessment and method statement for the site-specific diving work shall be conducted taking into consideration all the basic requirements. The risk assessment method statements (RAMS) shall be written in compliance with the national diving legislation.

National standards for worker safety under water shall be adhered to, when present. In the absence of such standards, it is recommended to comply with standards from the International Marine Contractors Association (IMCA). To perform a risk assessment for diver safety, IMCA HSSE 021 is recommended as guidance. The risk assessments shall include various risk scenarios that depend on the specific environment. Divers, who may get into contact with electrical current under water, shall follow guidelines and requirements in AODC 035.

Guidance note:

For further guidance on diving activities for FPV projects, the following practices may be used as a reference:

- IMCA D 010 High voltage training: A syllabus for training offshore workers involved with high voltage equipment
- IMCA D 018 Rev.1 Code of Practice for the initial and periodic examination, testing and certification of diving plant and equipment
- IMCA D 021 Rev.1 Diving in contaminated waters
- IMCA D 023 Diving Equipment Systems Inspection Guidance Note for Surface orientated (air) diving systems
- IMCA D 045 Code of practice for the safe use of electricity underwater
- IMCA D 039 FMEA (Failure Modes & Effects Analyses) for diving systems including aspects of life support for divers
- IMCA D 040 DESIGN for mobile/portable surface supplied systems
- DMAC 02 In-water diver monitoring
- DMAC 08 Thermal stress in relation to diving
- DMAC 11 Provision of first aid and the training of divers, supervisors and members of dive teams in first aid.

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11.2.9 Boats

Boats that are used during the installation, maintenance or access to the FPV array, shall be appropriate for their intended use and for carrying weight. Standards for boat safety requirements can be applied using the categories mentioned in [11.2.2]. That implies that a safe boat for risk category C (inshore) shall be designed to safely transport workers with a wind speed of up to 6 Beaufort and with wave heights of up to 2 meters.

The required stability level for the boats shall be appropriately determined in relation to their operational environment. Boats that are used to carry heavy loads should be equipped with a stability book which contains the maximum carrying weight in relation to down-rating environmental factors (waves and wind speeds).

It is recommended to include the categorisation of boats into the worker safety plan. Aspects regarding the lifting (over an angle) of equipment on/from boats should be also included in the lift plan.

11.2.10 External safety

External safety is a common risk factor in regular PV projects, that includes trespassing and injury by passers-by. The site of an FPV project should be fenced, if possible.

A risk assessment for an FPV project shall include external safety risks derived from:

- (the combination of) electricity and water
- possibilities to fence off the project
- recreational visitors
- the fencing-off of the project.

It is recommended to comply to the EC Directive 92/58/EEC (EU-OSHA), or any equivalent local or national standard, for health and safety signs and lights. Appropriate signage shall be in place where hazards cannot be avoided or reduced. Project plans should, at least, contain provisions to inform visitors and passer-by of risk of injury, emergency escape, first-aid, fire hazards and hazardous moving parts.

It is recommended to install signs to manage external safety both on the FPV system, as well as on the land near the FPV system and in proximity of any onshore electrical components.

11.2.11 Electrical safety

To minimize electrical safety risks, electrical layout of an FPV system shall be designed following the requirements and guidelines contained in Sec.8.

To minimize electrical safety risks during installation and O&M procedures, requirements and guidelines contained in [9.2.2] and [9.3.2] respectively shall be followed.

SECTION 12 LEVELISED COST OF ELECTRICITY

12.1 General

A common way of representing costs associated with a PV project, or a project in general, is by using the figures of capital expenditures (CAPEX) and operational expenditures (OPEX).

CAPEX is normally expressed in cost unit [CU] or in cost unit per installed capacity [CU/kWp].

OPEX is normally expressed in cost unit over the lifetime of the project [CU] or in annual cost unit [CU/year] or in annual cost unit per installed capacity [CU/kWp/year].

For PV projects in general, and FPV projects, the amount of revenues depends not only on the installed capacity, but eventually on the electricity generation. Hence, in addition to the sole figures of CAPEX and OPEX, a relevant economic parameter that should be assessed for any FPV project is the levelised cost of electricity (LCOE).

The LCOE is a measure of the average net present cost of electricity generation for a generating plant over its lifetime, by using a combination of CAPEX, OPEX and the (expected) power plant’s electricity production. The LCOE is expressed in cost unit per energy unit produced [CU/kWh].

12.2 Calculation of levelised cost of energy

12.2.1 General

The LCOE may be calculated by taking the net present value of the total cost of building and operating a power generating asset and then dividing by the total discounted electricity generation over its lifetime, as in the following well-known formula:

$$LCOE = \frac{CAPEX_0 + \sum_{t=1}^{n} \frac{OPEX_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}}$$

where:

$CAPEX_0$ = capital expenditures in year 0 in relevant cost unit [CU]

$OPEX_t$ = annual operational expenditures in year t, in relevant cost unit [CU]

E_t = electricity production of the FPV system in year t, in [kWh]

i = capital discount rate in [%]

n = lifetime of the FPV project, in [years]

t = year within the FPV project lifetime (1 to n).

The following subsections describe which cost components should be included in the variables of the LCOE formula for FPV projects.

Guidance note:

These recommendations are meant to be instructive in order to use the correct methodology and cost components, not to provide ranges or specific cost or yield factors associated with single project’s circumstances, as they vary consistently in location and in time, due to specific site conditions and to market developments.

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12.2.2 Capital expenditures

The capital expenditures for FPV projects should include costs for the following items, where applicable, including but not limited to:

- station-keeping system, including anchors, mooring lines and connection with floating structure
- floats
- mounting structure
- PV modules
- BoS (e.g. inverters, cables, combiner boxes, transformer, monitoring equipment, security equipment, etc.)
- labour for installation
- fuel and electricity costs related to installation equipment and procedures
- grid connection costs
- land and water acquisition costs (if not leased)
- others (development costs, permit fees, etc.).

12.2.3 Operational expenditures

The operational expenditures of FPV projects shall be determined for the entire lifetime of the project and shall include costs for the following items, where applicable, including but not limited to:

- general O&M costs
- labour costs for O&M
- fuel and electricity costs related to O&M equipment and procedures
- monitoring costs
- cleaning
- site lease (if applicable)
- acquisition and installation of spare parts
- asset management.

12.2.4 Discount rate

The discount rate refers to the rate that is used in the discounted cash flow analysis for determining the present value of future cash flows and electricity production of the project.

12.2.5 Lifetime of the project

The lifetime of the FPV project is the number of planned operational years of the FPV project and shall be representative of the expected durability of the components, eventually including substitution of components at their end-of-life, if properly accounted for in the cost components.

12.2.6 Electricity generated

The amount of expected electricity generated over the lifetime of an FPV project shall be assessed following the methodology and procedures described in Sec.3.

It is important to keep into consideration that the electricity generated each year is not expected to be constant. In addition to yearly variations, system degradation shall be taken into account, as described in [3.8.5].

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Table 13-1 Bibliography

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APPENDIX A WAVE-INDUCED MISMATCH LOSSES CALCULATION EXAMPLE

This appendix contains indicative guidance and a conceptual methodology on how to calculate wave-induced mismatch losses. Wave-induced mismatch losses are introduced in the EYA of FPV projects, see [3.7.2.2].

Any given PV string may be subject to wave motion that could perturb any PV module on that string within a +/- 2° range on both the tilt and azimuth axis (wave intensity, float and mooring and anchoring technology dependant).

In order to understand the effect a +/- 2° perturbation may have on a string and ultimately annualised energy, one technique is to simulate a set of ‘off tilts’ and ‘off azimuths’ relative to the project's design parameters.

For example, to estimate the wave-induced mismatch losses of a 10° fixed tilt FPV system with an estimated +/- 2° wave induced perturbation, the following methodology may be implemented:

1) Generate an hourly production profile (8760 hours) for each permutation within the +/- 2° range. For this example the range of tilts would be: [8°,9°,10°,11°,12°] and range of azimuths would be: [-2°,-1°,0°,+1°,+2°], resulting in 30 hourly production timeseries.
2) On an hourly basis, determine the datapoint with the lowest output energy from these 30 timeseries.
3) Synthesise a new hourly timeseries which selects for the lowest hourly datapoint energy over the range of tilts and azimuth simulation runs.
4) This synthesised timeseries represents the power output resultant of the wave-induced mismatch.

Important assumptions to this method are: at any moment, any string has a PV module that is at the most unfavourable tilt/azimuth within a wave intensity dependent interval.

Improvements to this method may include:

- Estimating string energy by using a value that is not necessarily the lowest performing (e.g. taking the P90 energy value of the string to define the string).
- Inclusion of seasonality (e.g. long term windspeed averages at some periods in the year may be more conducive to heightened wind speeds and thus tilt/azimuth simulation ranges).

CHANGES – HISTORIC

There are currently no historical changes for this document.