Optimization of Offshore Wind Farm Collection Grids: Hybrid Transmission Systems and AI-driven Substation Placement

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TNO innovation for life

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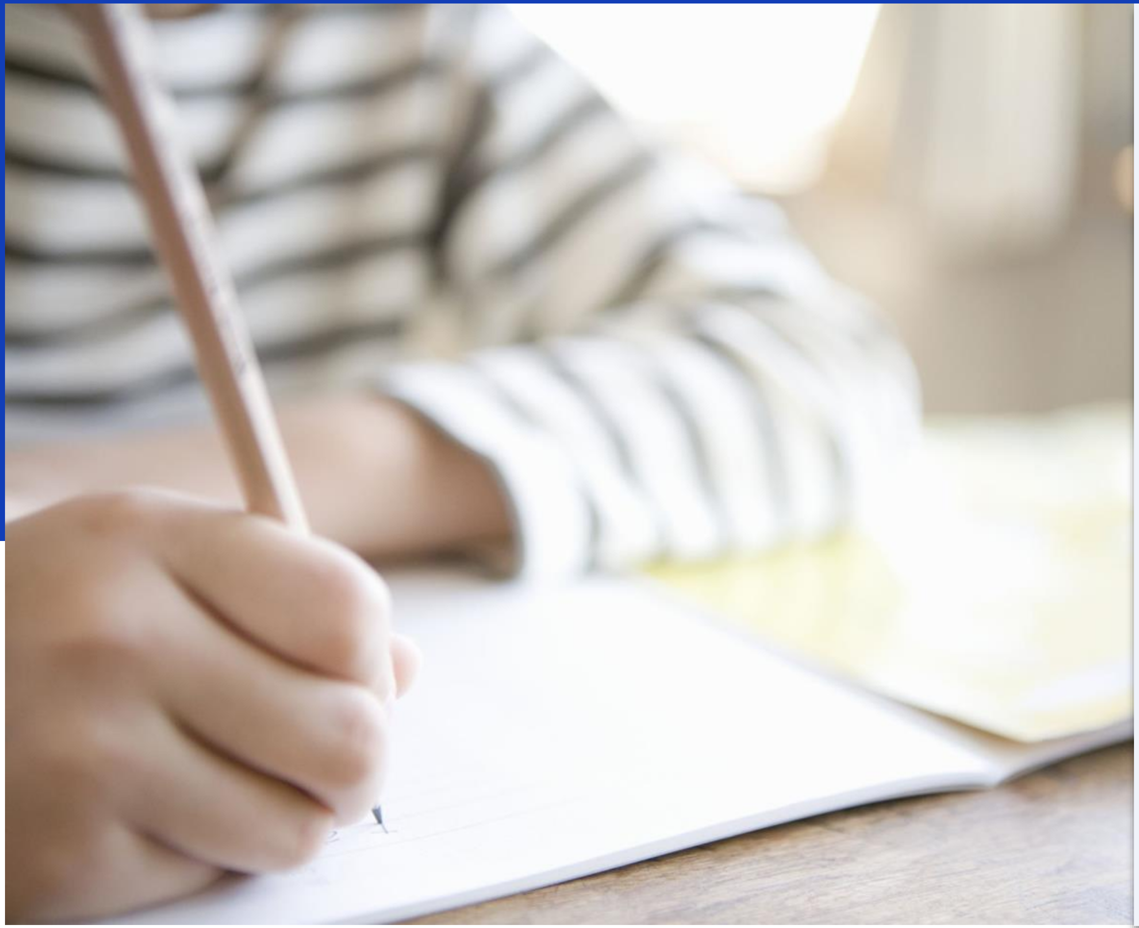
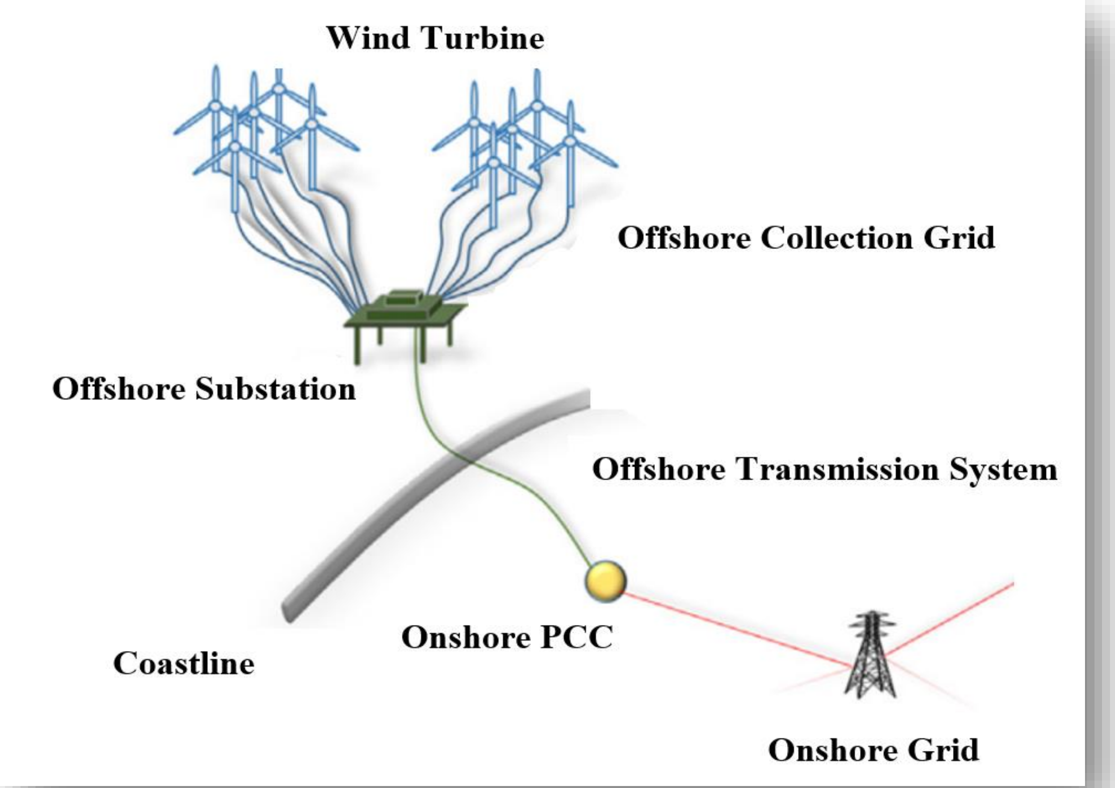


Introduction:

Problem Definition and Main Goals:

- The **collection grid** of an offshore wind farm consolidates electricity from turbines and ensures efficient transmission to shore
- The main aim of this study is to **enhance the efficiency, cost-effectiveness, and reliability** of offshore WF collection grids
- It investigates **emerging trends** in offshore WF collection grid configurations, **optimal substation placement**, and **hybrid HVAC/HVDC** transmission systems to improve design and operation
- The ultimate goal is to **design flexible and resilient configurations** for large-scale offshore wind energy systems



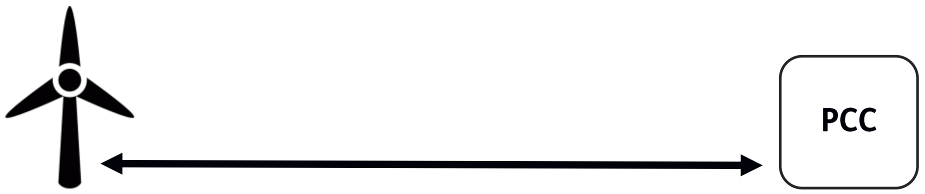
Literature Survey

Offshore Wind AC Collection Grid Topology:

- AC collection grids have become the **standardized** approach in constructing offshore wind farms.
- The primary topologies identified include **radial, ring, and star configurations**
- Some **hybrid or composite topologies** have been introduced, which indicate the potential for **innovative design** approaches
- The hybrid topologies are generally **variations of these primary models**
- The critical components of AC collection grids are **cables, connectors,**

and **transformers**

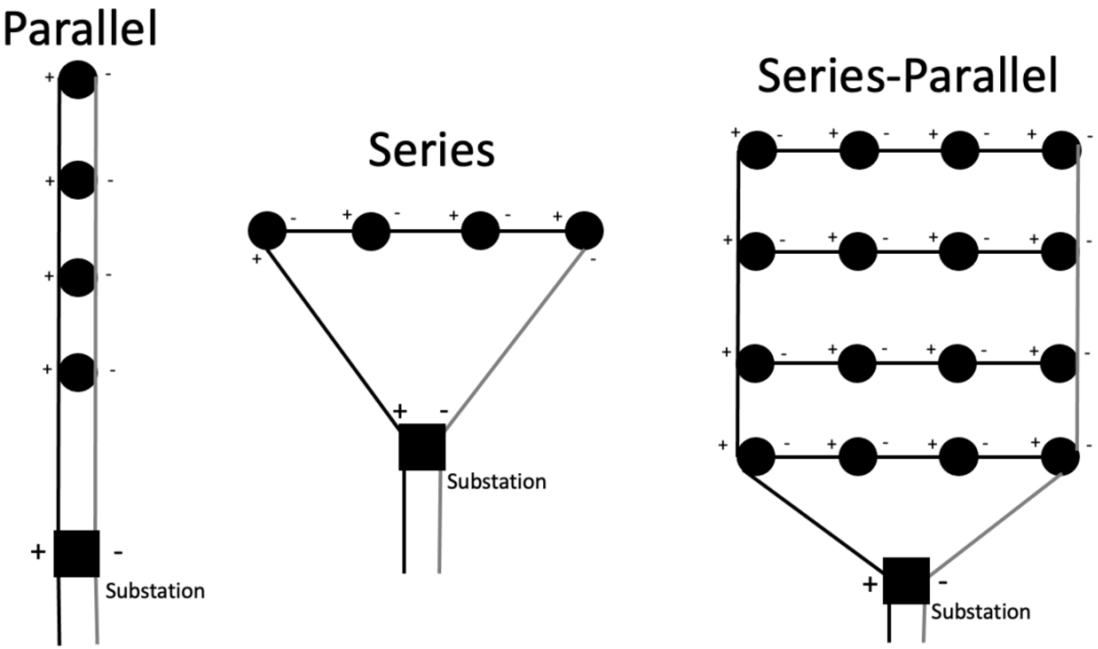
- Choosing an appropriate topology is influenced by various factors, such as **<u>the capacity of the wind farm</u>**, **<u>its distance to the mainland grid</u>**, and the **<u>system's reliability standards</u>**

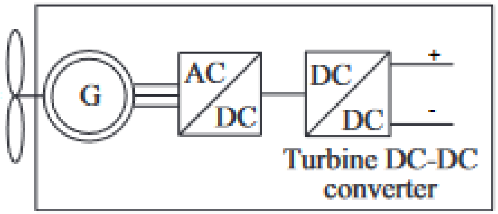


Literature Survey

Offshore Wind DC Collection Grid Topology:

- There are **<u>three</u>** DC collection grid topologies, including **parallel, series, and series-parallel**





AC or DC?

If transmission is **HVDC**:
conversion from a medium voltage AC grid to an HVDC transmission system requires the use of complex equipment, so **DC would be beneficial**

Problem Modeling

Optimization Problem for Modeling the Offshore Wind Farm Substation Placement and Cable Routing:

- Mixed-Integer Linear Programming (MILP) optimization
- The **primary objective** is to **minimize** the **total cost**, which includes both **investment and operational expenses**, and to **maximize** the **total revenue**
- This must be achieved while ensuring **all technical constraints** and **avoiding cable crossings**

Data Collection:

- **Power Curve Data:** We currently use the power curve data of a 4 GW wind farm located at **IJmuiden Ver** in the Netherlands
- **Wind Speed and Direction Data & Energy market prices:** For a few **representative days** are used

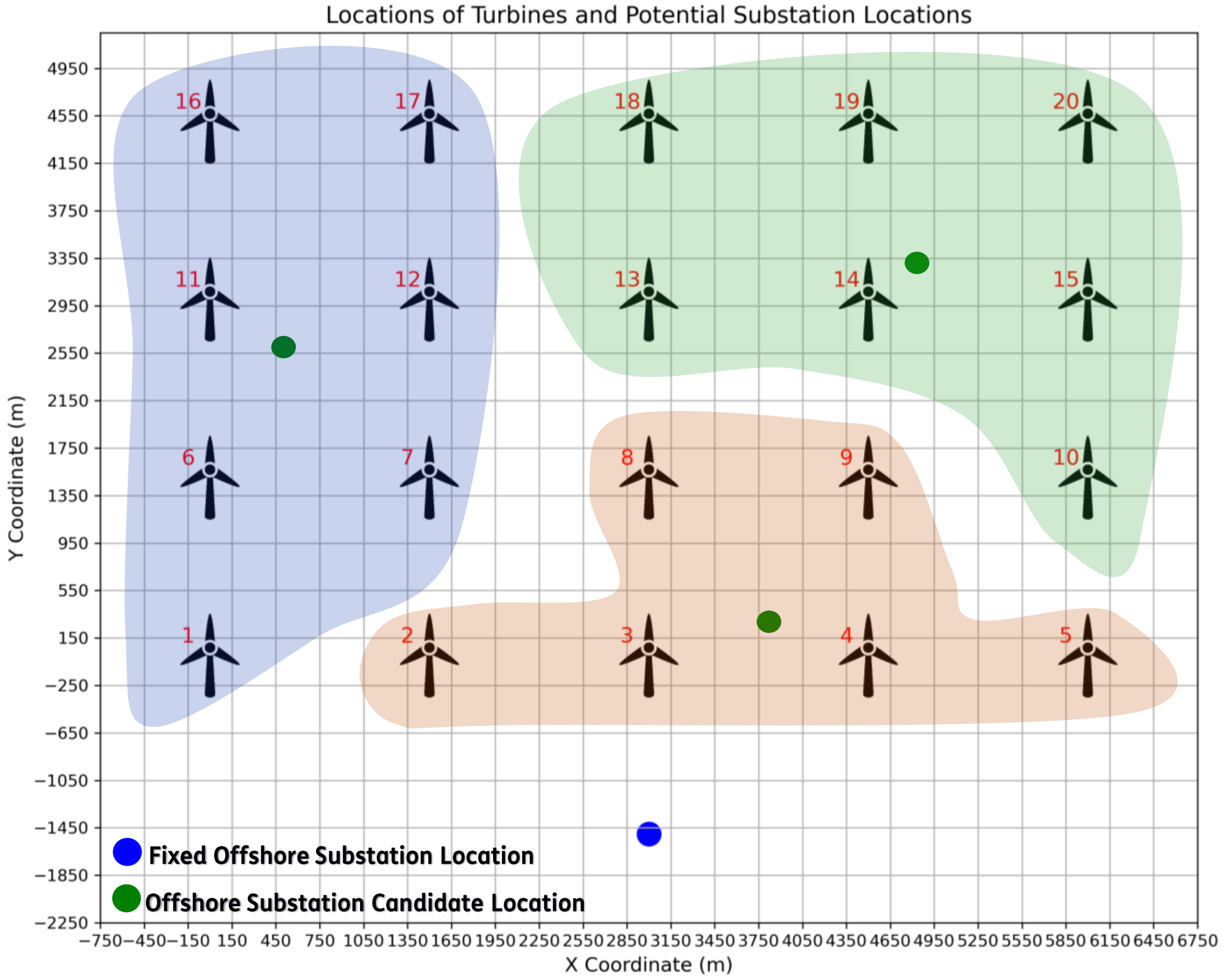
Problem Modeling

Optimization Problem for Modeling the Offshore Wind Farm Substation Placement and Cable Routing:

- The considered offshore wind farm consists of turbines arranged in a grid layout **to optimize wind capture** and **minimize wake effects**

  Number of turbines: **20 (each with a 20 MW Cap.)**
  Arrangement: **4 rows and 5 columns**
  Distance between turbines: **1500 meters**
  Distance between rows: **1500 meters**

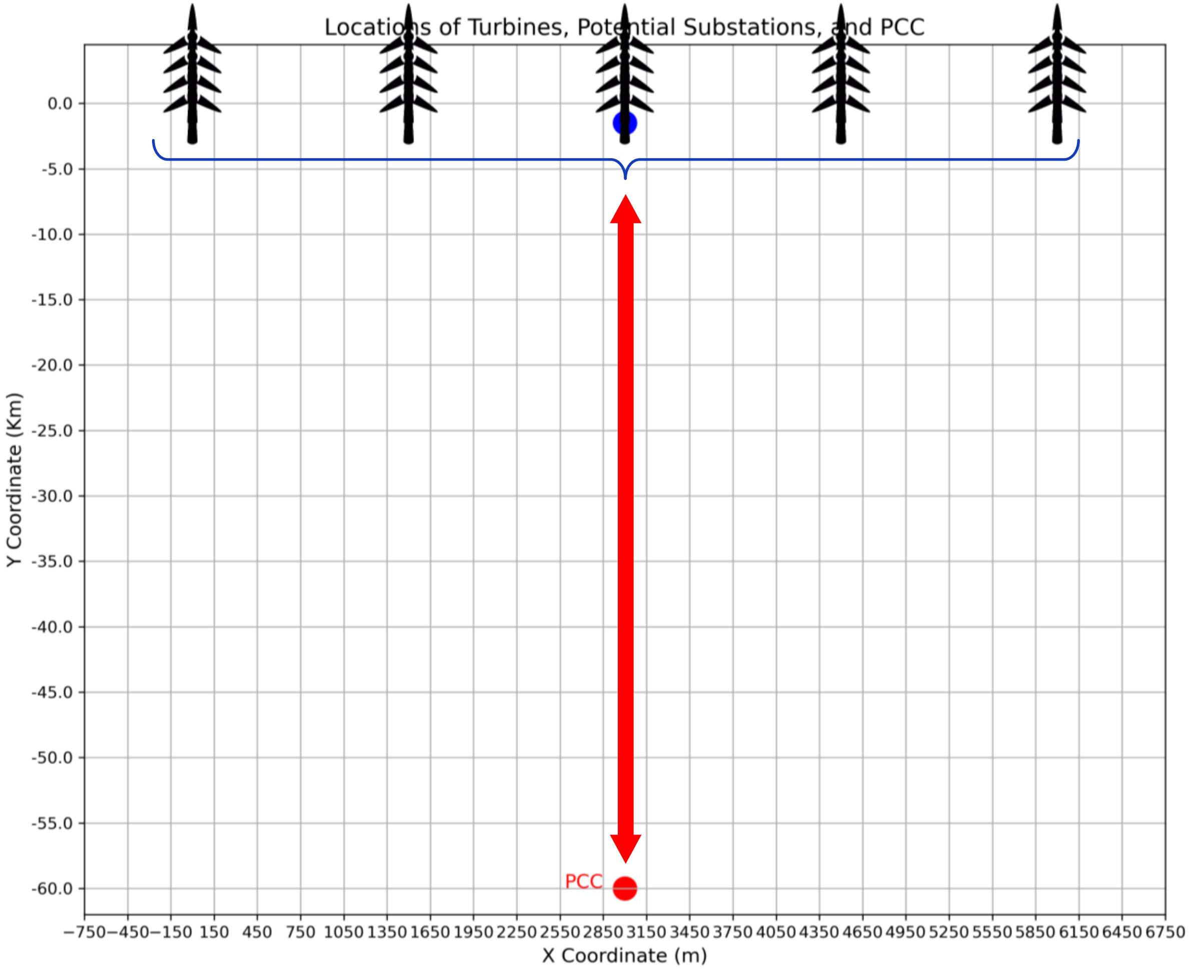
- The offshore fixed substation location is positioned **centrally** relative to the turbines and slightly offset, based on **the average position of the turbines**
- The rest of best candidate location are obtained using **clustering** to group the turbines based on their **coordinates**



Problem Modeling

Optimization Problem for Modeling the Offshore Wind Farm Substation Placement and Cable Routing:

- The point of common coupling (**PCC**) is located **onshore**, and the offshore substation can be connected to it through transformers and **long <u>high-voltage AC or DC</u> cables**
- The PCC is a **fixed** point onshore (≈**60 Km** distance)
- To evaluate the considered hybrid **HVAC/HVDC** transmission system, the PCC distance can be changed up to **100 Km**



Problem Modeling

Optimization Problem for Modeling the Offshore Wind Farm Substation Placement and Cable Routing:

Mathematical Formulations: Objective Function and Technical Constraints

- The objective is to minimize the total cost, including both investment and operational costs, and to maximize the revenue from selling power at the PCC location

$$\min \quad \textbf{Investment Cost} + \textbf{Operation Cost} - \textbf{Revenue}$$

List of Technical Constraints:

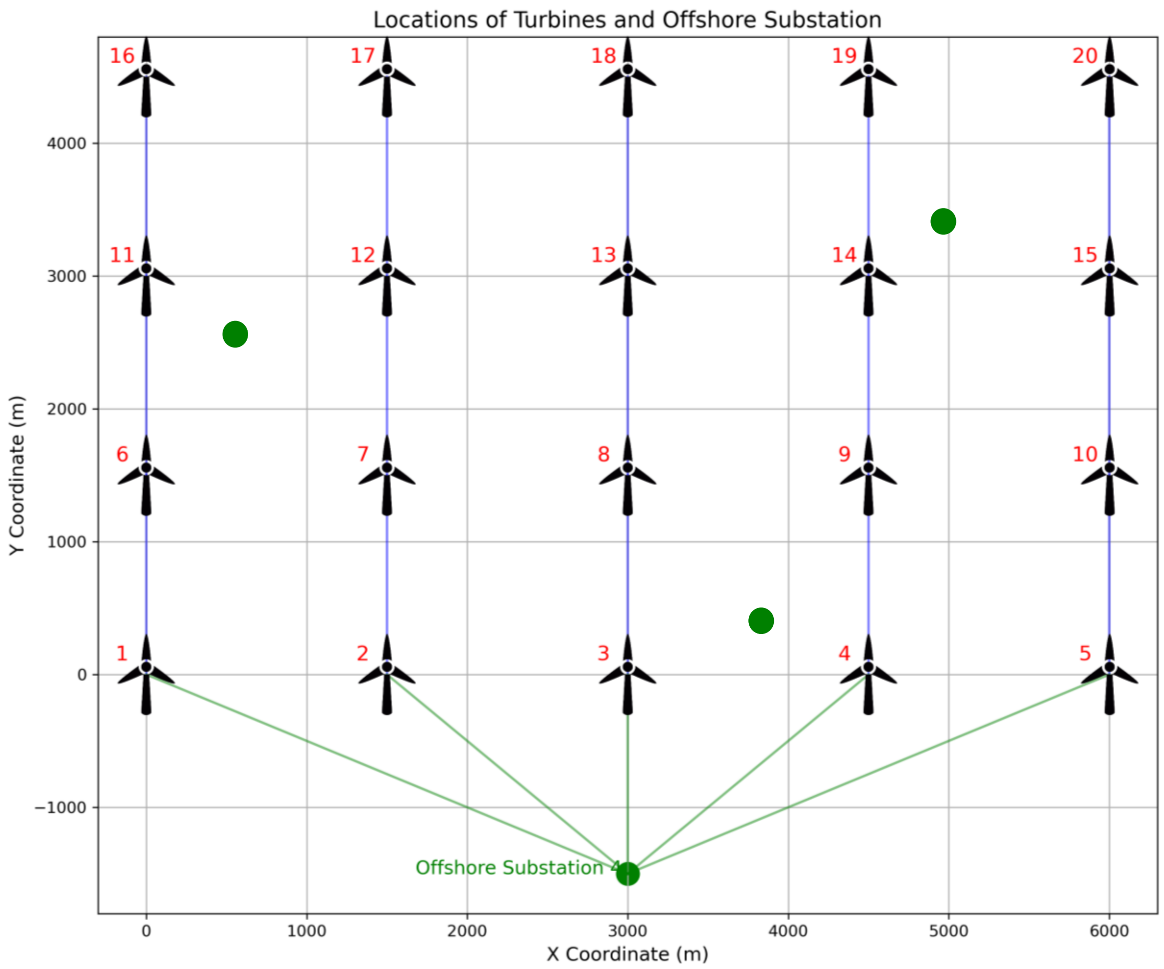
- Power Balance Constraint for each Turbine
- Offshore Substation Power Balance Constraint
- Total Transferred Power to PCC Constraint
- MV & HV Cables Power Flow Constraints
- VSC coupling constraints
- Offshore Substation Location Constraints
- Linearization of Cable & VSC Power Losses
- Transformer and Cable Type Constraints
- Constraints to Avoid Cable Crossings
- Auxiliary Constraints for Acceleration of the Code

Numerical Results

Base Case (Radial):

A **fixed** & **multiple** offshore substations

Total Cost & Revenue Component	Value (K€)
Annualized Investment Cost	10,275.37
Loss Cost (HV Cables)	615.96
Loss Cost (HVDC Cables)	0
Loss Cost (HVDC VSC)	0
Wind Curtailment Cost	0
Revenue from Energy Sales	69,055.38
Operation Cost	615.96
Revenue - Cost	58,164.05



Numerical Results

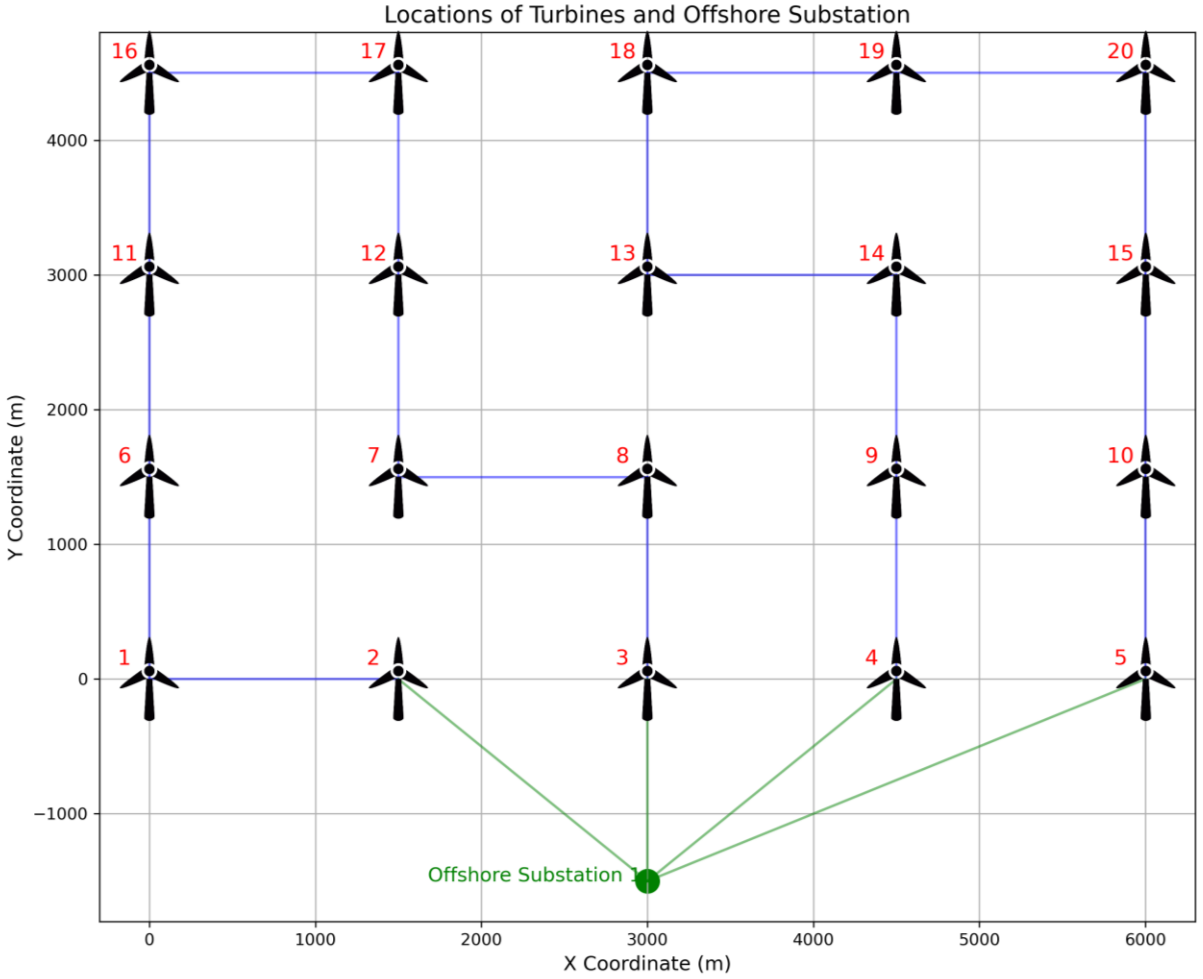
Ring Connection Configuration:

A **fixed** offshore substation

List of Additional Constraints:

- Modifying some of the existing constraints
- Adding a new constraints to ensure ring configuration

Total Cost & Revenue Component	Value (K€)
Investment Cost	10,412.46
Loss Cost (HV Cables)	615.96
Loss Cost (HVDC Cables)	0
Loss Cost (HVDC VSC)	0
Wind Curtailment Cost	0
Revenue from Energy Sales	69,055.38
Operation Cost	615.96
Revenue - Cost	58,026.96

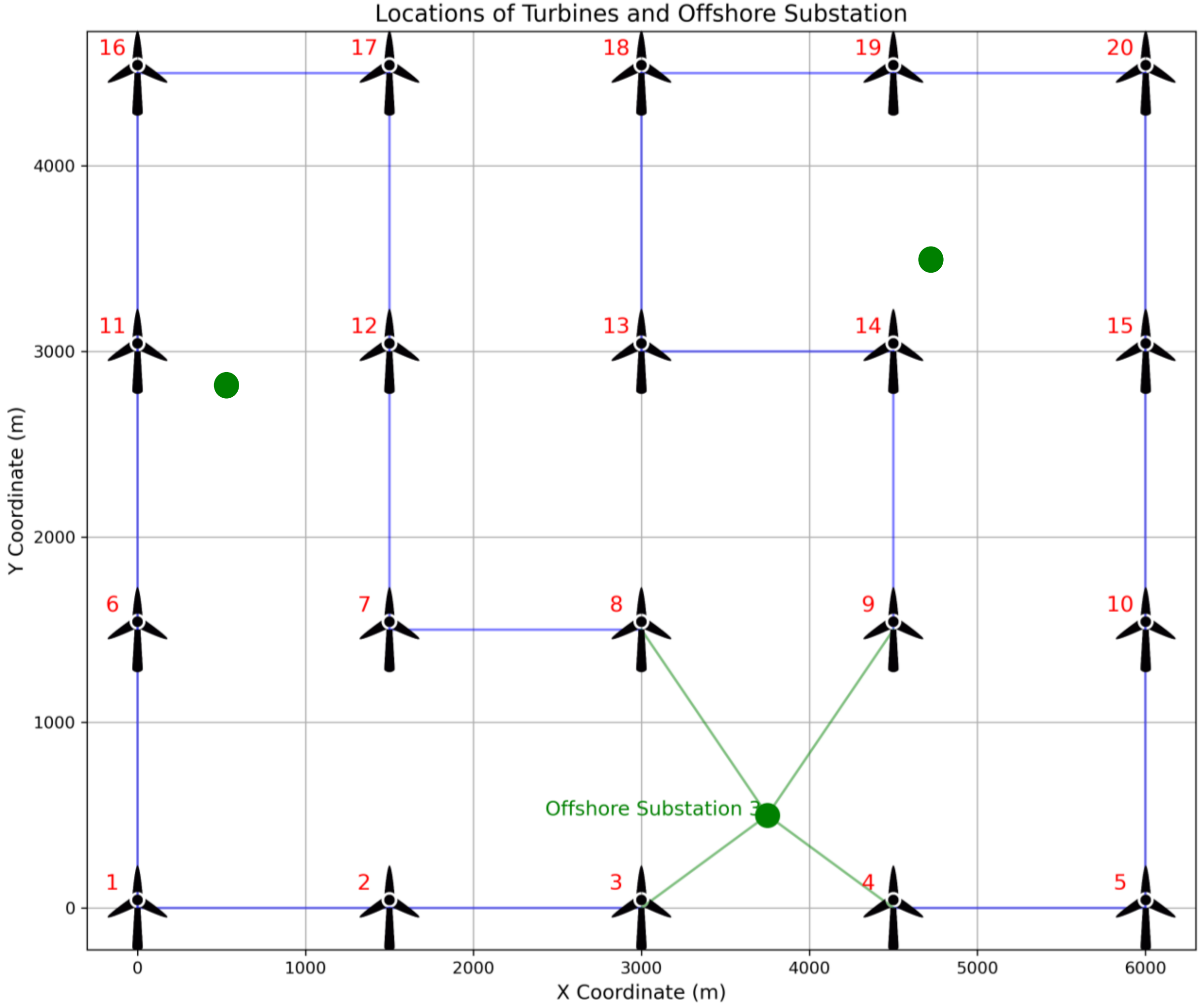


Numerical Results

Ring Connection Configuration:

Multiple offshore substations

Total Cost & Revenue Component	Value (K€)
Investment Cost	10,373.24
Loss Cost (HV Cables)	637.07
Loss Cost (HVDC Cables)	0
Loss Cost (HVDC VSC)	0
Wind Curtailment Cost	0
Revenue from Energy Sales	69,038.74
Operation Cost	637.07
Revenue - Cost	58,028.43



Numerical Results

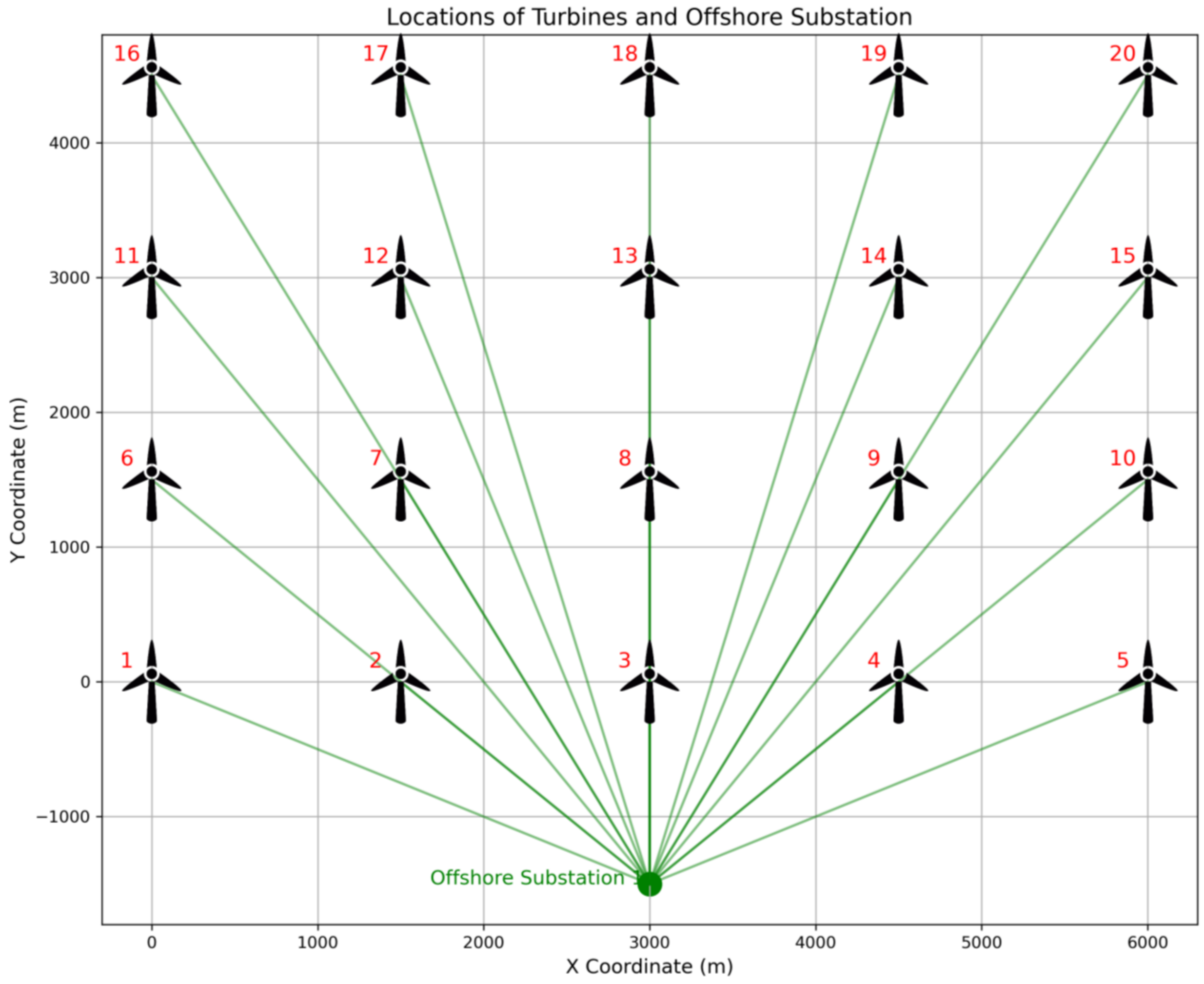
Star Connection Configuration:

A **fixed** offshore substation

List of Additional Constraints:

- Modifying some of the existing constraints
- Adding a new constraints to ensure star configuration

Total Cost & Revenue Component	Value (K€)
Investment Cost	12,371.52
Loss Cost (HV Cables)	615.96
Loss Cost (HVDC Cables)	0
Loss Cost (HVDC VSC)	0.00
Wind Curtailment Cost	0
Revenue from Energy Sales	69,055.39
Operation Cost	615.96
Revenue - Cost	56,067.91

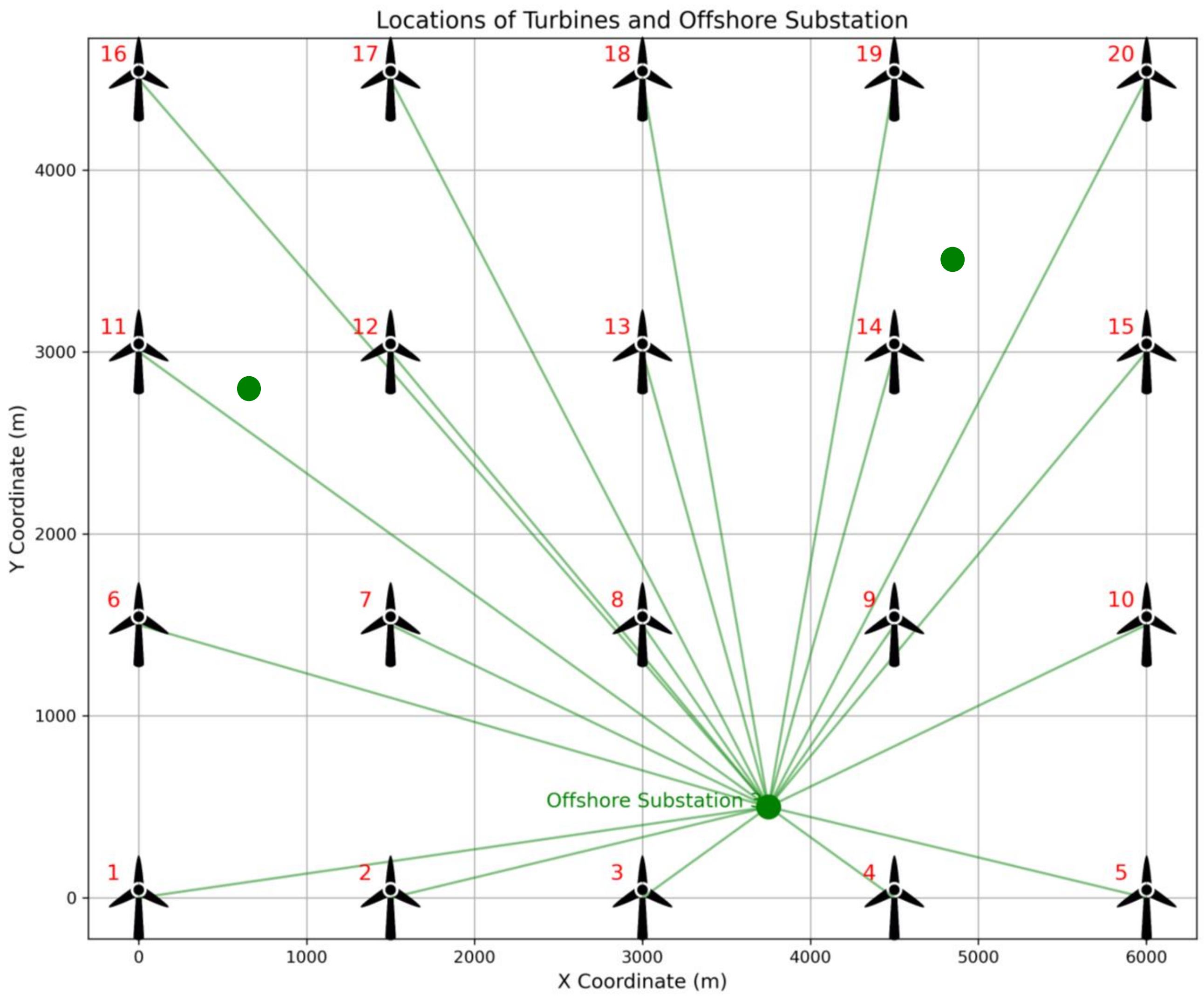


Numerical Results

Star Connection Configuration:

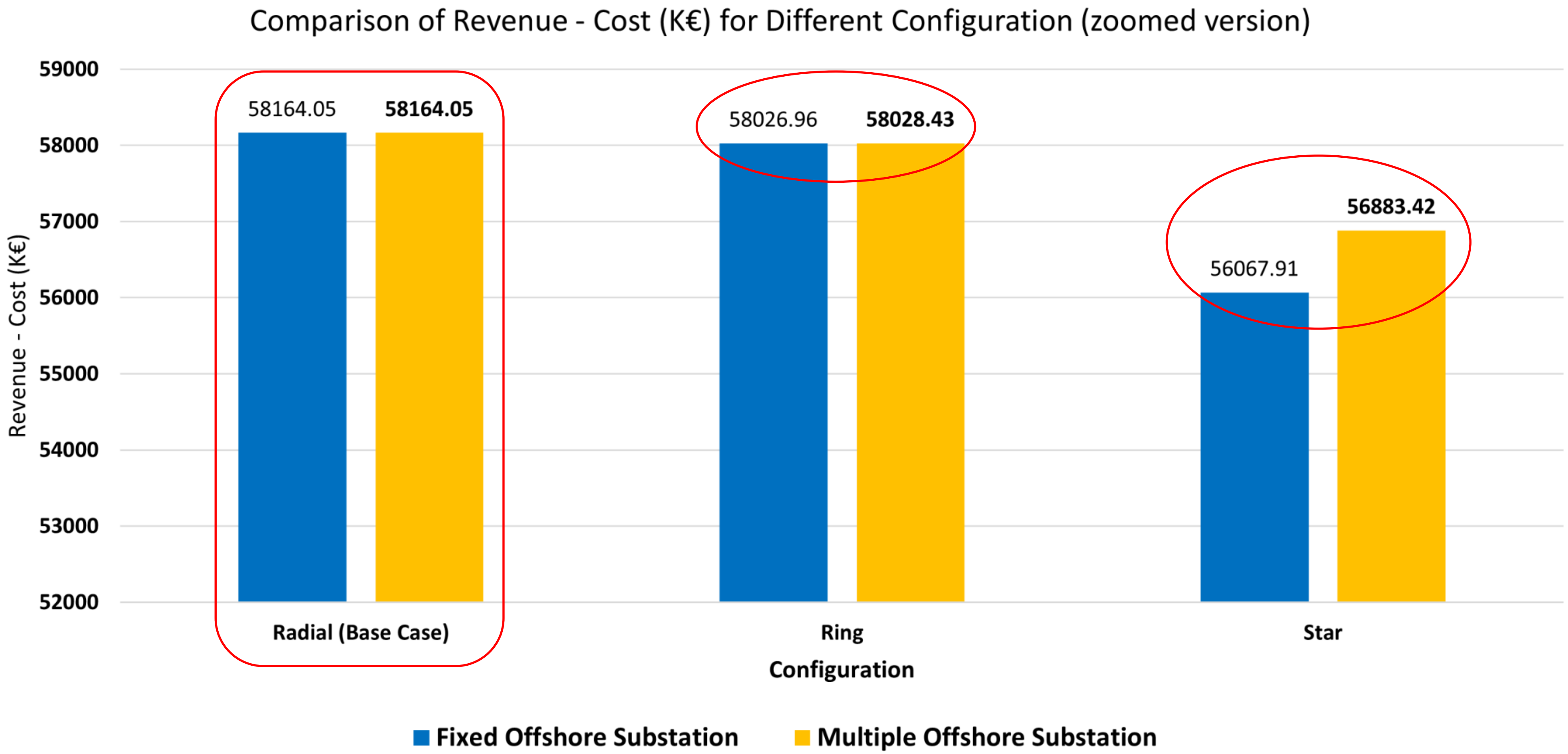
Multiple offshore substations

Total Cost & Revenue Component	Value (K€)
Investment Cost	11,518.25
Loss Cost (HV Cables)	637.07
Loss Cost (HVDC Cables)	0
Loss Cost (HVDC VSC)	0.00
Wind Curtailment Cost	0
Revenue from Energy Sales	69,038.74
Operation Cost	637.07
Revenue - Cost	56,883.42



Numerical Results

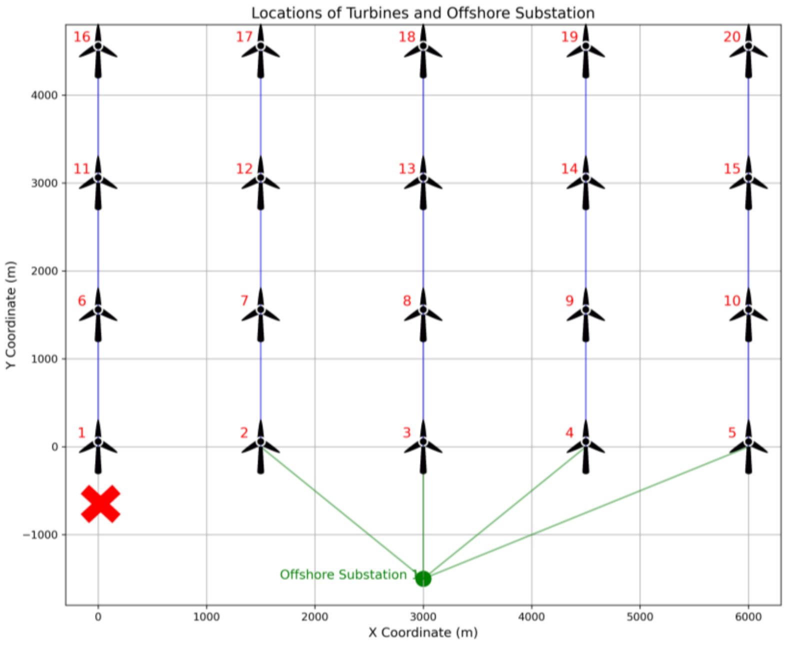
Comparing the Results

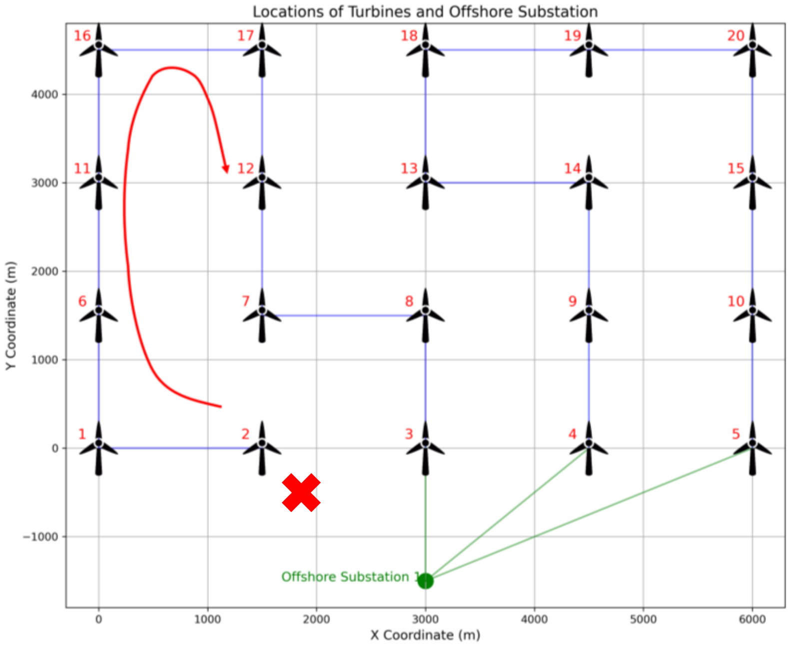


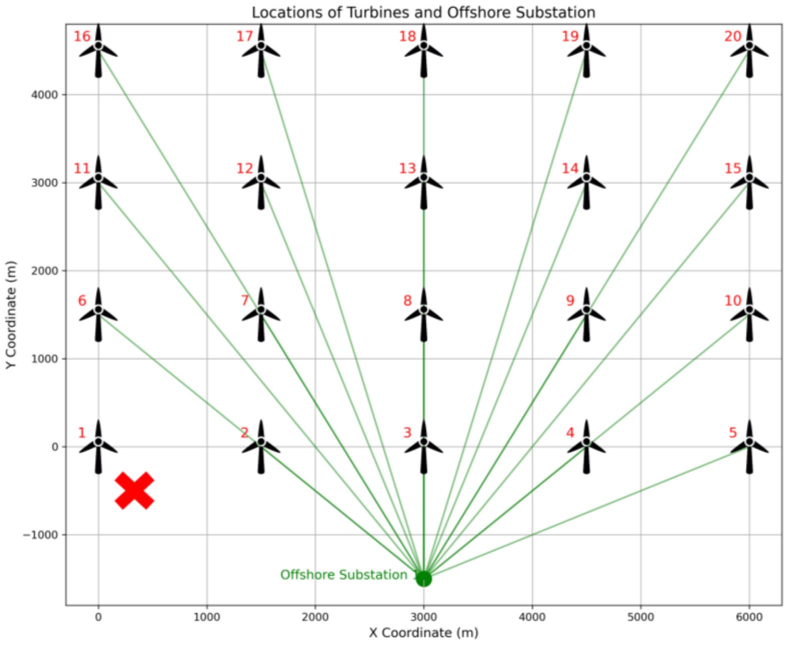
Numerical Results

- **Reliability Assessment**

We assumed **two failures per year**, each resulting in **20 days** of interruption = 2 × 20 × 24 **= 960** hours / year

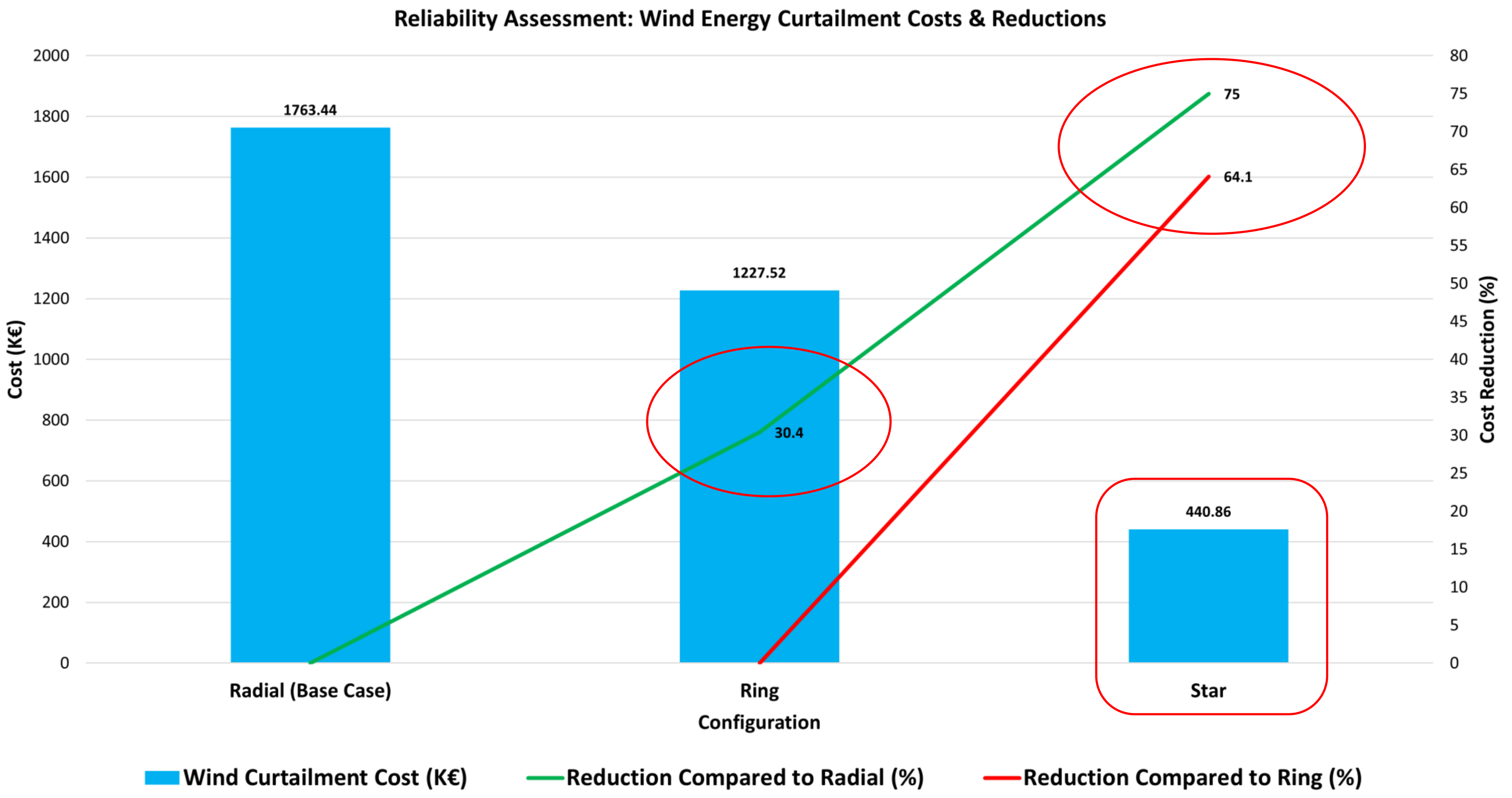






Numerical Results

- Reliability Assessment



Numerical Results

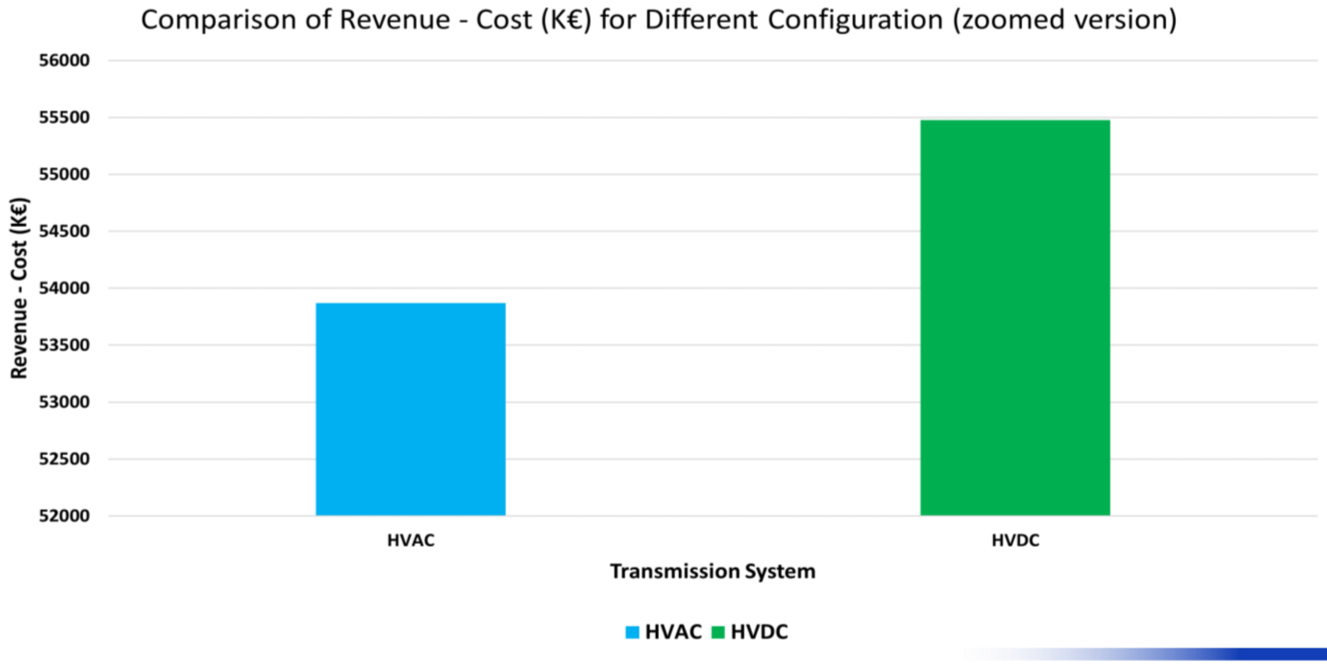
- Remote Offshore Wind Farm with **HVAC/HVDC** Transmission System: **95 Km distance to PCC**

HVAC

Total Cost & Revenue Component	Value (K€)
Investment Cost	13,911.78
Loss Cost (HV Cables)	984.48
Loss Cost (HVDC Cables)	0
Loss Cost (HVDC VSC)	0.00
Wind Curtailment Cost	0
Revenue from Energy Sales	68,764.63
Operation Cost	984.48
Revenue - Cost	53,868.37

HVDC

Total Cost & Revenue Component	Value (K€)
Investment Cost	12,940.21
Loss Cost (HV Cables)	0.00
Loss Cost (HVDC Cables)	123.87
Loss Cost (HVDC VSC)	486.26
Wind Curtailment Cost	0
Revenue from Energy Sales	69,027.07
Operation Cost	610.13
Revenue - Cost	55,476.73



Conclusion

1. **Optimized Grid Configurations:** Star layouts minimize energy curtailment during outages, but have high investment costs, radial layouts are the most cost-effective, and ring layouts balance reliability and cost.
2. **Strategic Substation Placement:** Strategic offshore substation placement lowers costs, and boosts revenue, making it essential for OWF design.

3. **HVDC vs. HVAC Transmission:** HVDC systems are more efficient for remote, large-scale offshore wind farms due to lower energy losses and superior long-distance performance.

Thanks for your attention

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