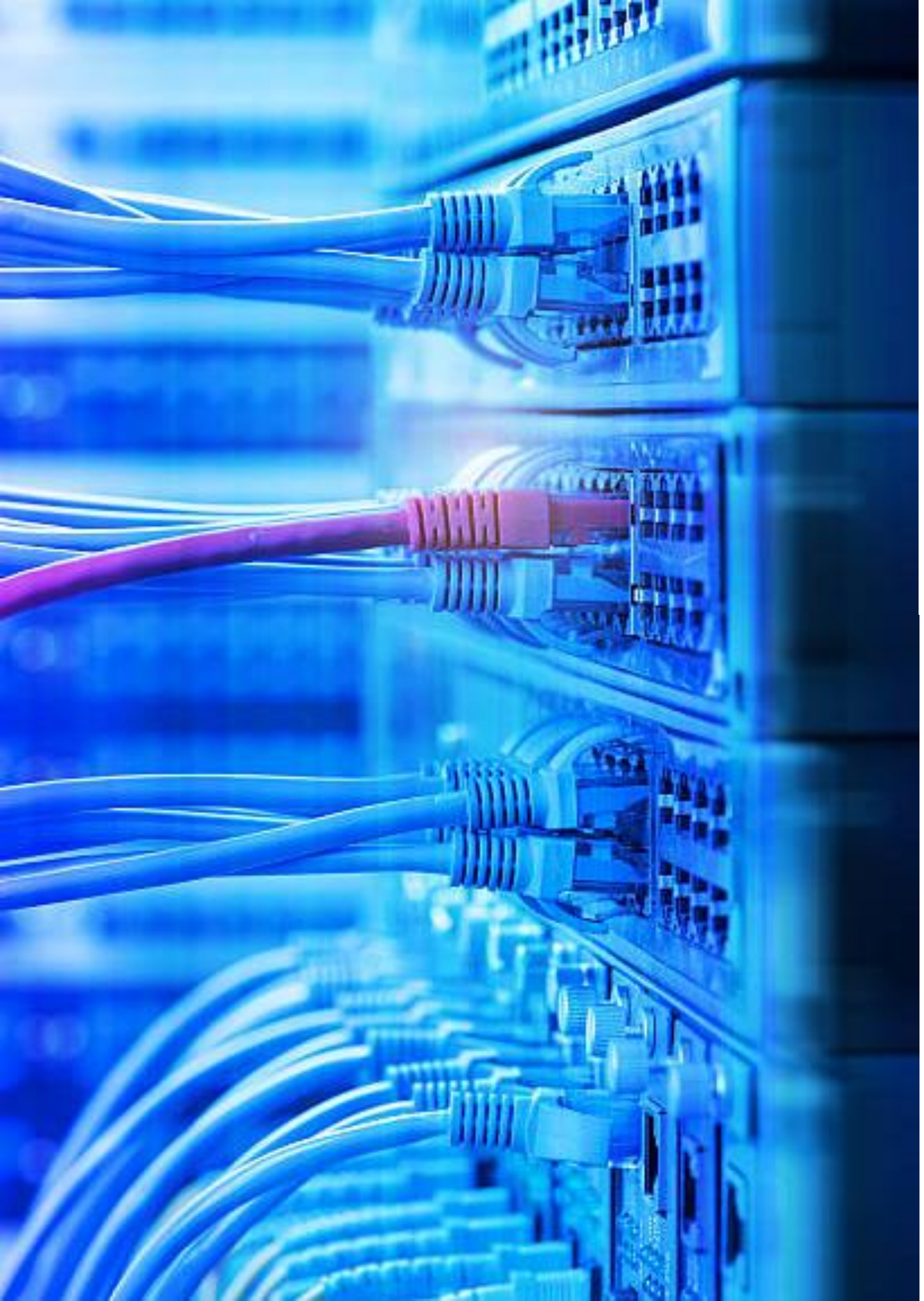


An Intent-based resource provisioning approach for Software-defined Industrial IoT-Edge networks.

Agrippina Mwangi, Ph.D. Candidate
Energy & Resources Group
Copernicus Institute of Sustainable Development
Utrecht University, The Netherlands

About Me

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

- Academic Background

Utrecht University

Ph.D. in Engineering
- Research Interests: IIoT-Edge architectures, SDN/NFV, AI/ML, autonomous networks, and offshore wind

MSc. Electrical and Computer Engineering
- Major: Advanced Network Technologies
- Minor: Applied ML and Data Analytics

- Professional Background

Safaricom
CARREL TECHNOLOGIES
CISCO CERTIFIED CCNA
CHECKUPS medical hub

AGRIPPINA MWANGI (Ph.D. Candidate)

Copernicus Institute of Sustainable Development
Utrecht University,
The Netherlands

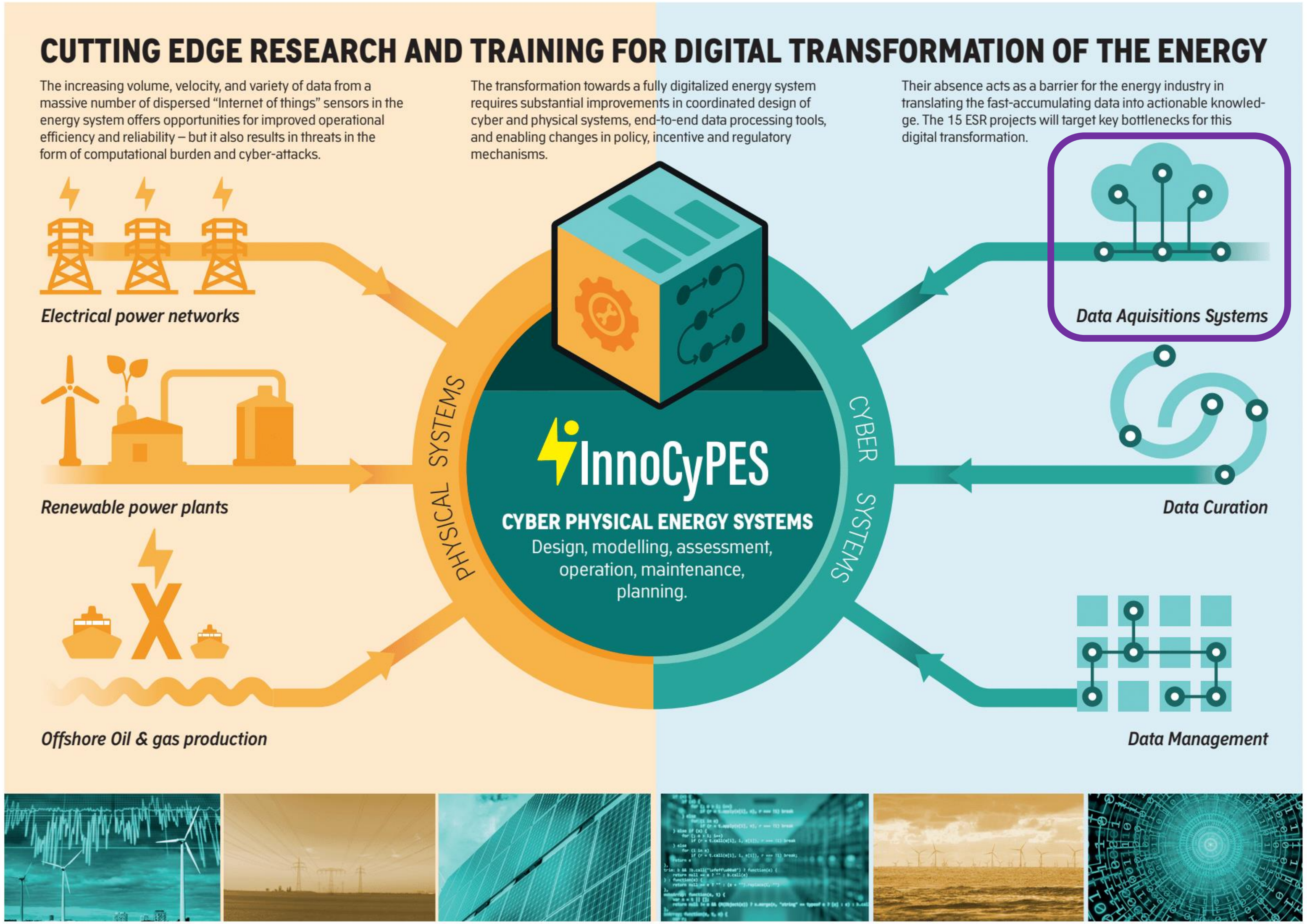
Innovative Tools for Cyber-Physical Energy Systems (InnoCyPES)

The overall goal of the project is to deliver a decision-making tool to enable energy companies to optimally design and utilize the ICT infrastructure and develop digital solutions, considering end-to-end data lifecycle and solution.

Research Work Scope: Data Acquisition Systems

Application Scenario: Offshore wind farms

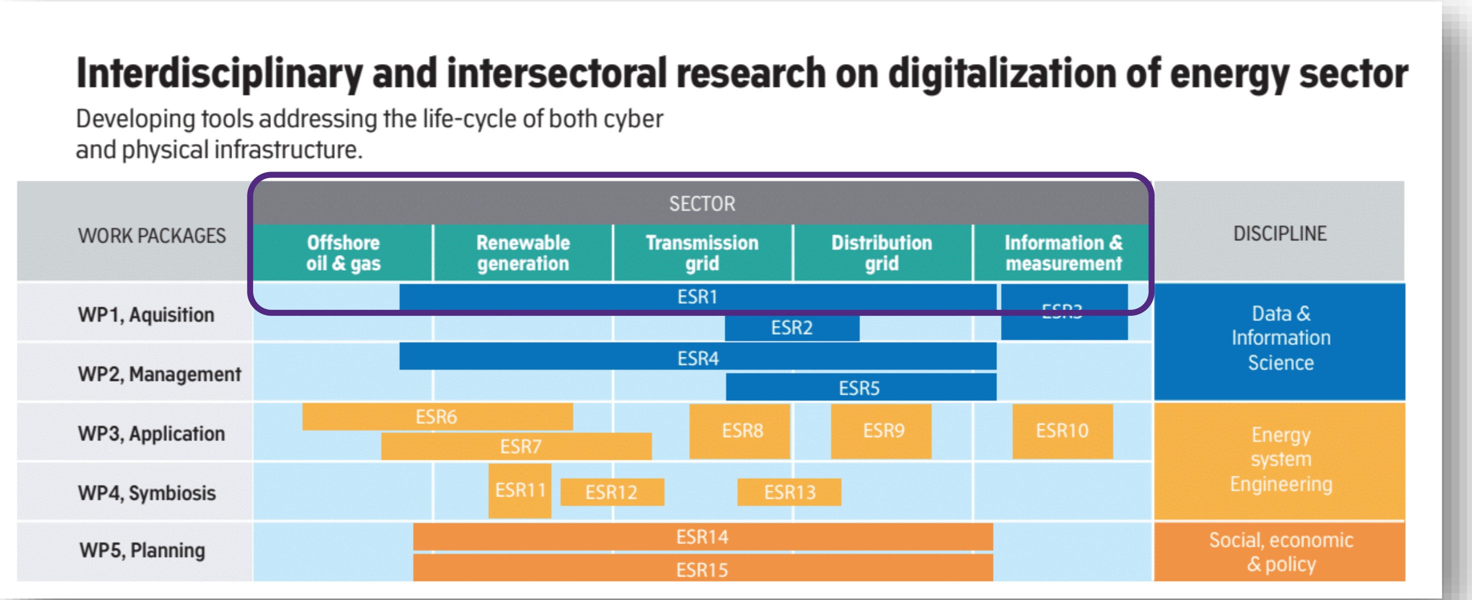
("wind farms of tomorrow")



This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska Curie grant agreement No. 956433.

Ørsted

Innovative Tools for Cyber Physical Energy Systems (InnoCyPES)



Host Institution:

Universiteit Utrecht

Key Partners and beneficiaries:

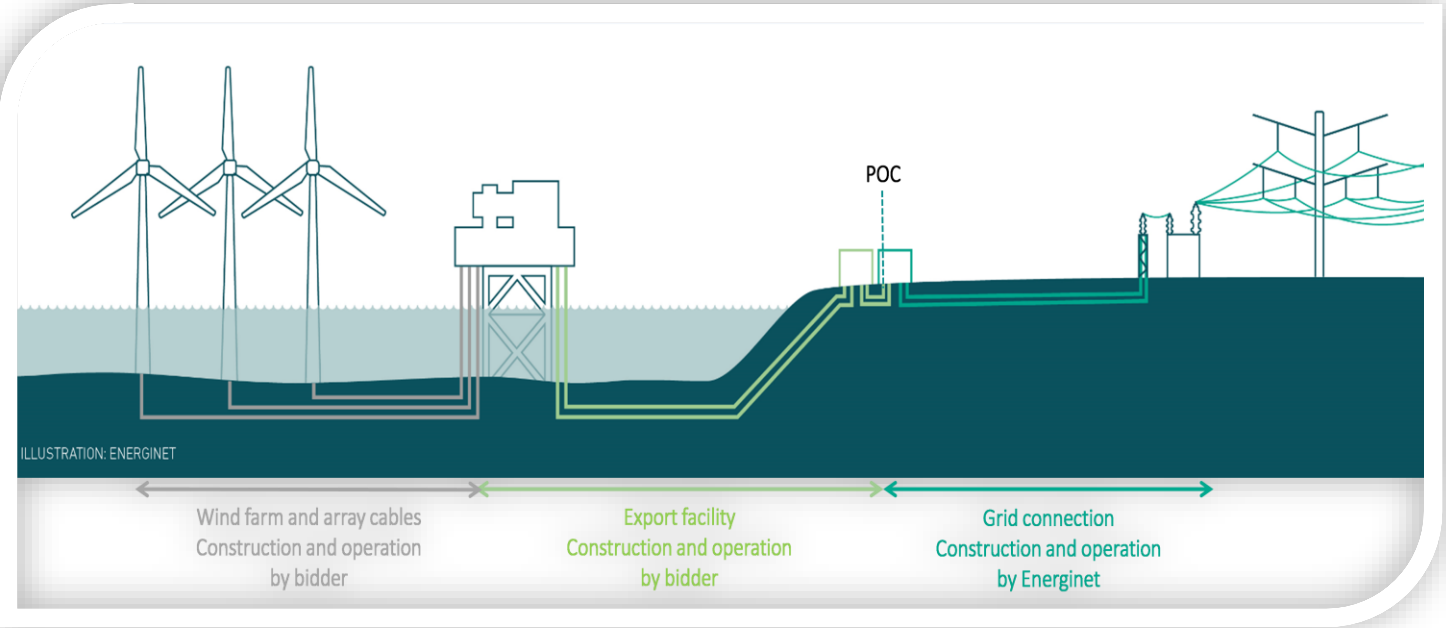
Ørsted EDF TUDelft

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956433.

Offshore Wind Farms

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

- Offshore wind farms are growing in complexity and size, expanding deeper into maritime environments to capture stronger and steadier wind energy.
- The intricacies of sea environments such as unpredictable weather patterns and the long distance from shore make manual monitoring and maintenance a logistical challenge and economically draining.
- Distance between individual WTGs and offshore substation (tens of kms). Distance between offshore substation and onshore substation or control room (hundreds of kms).

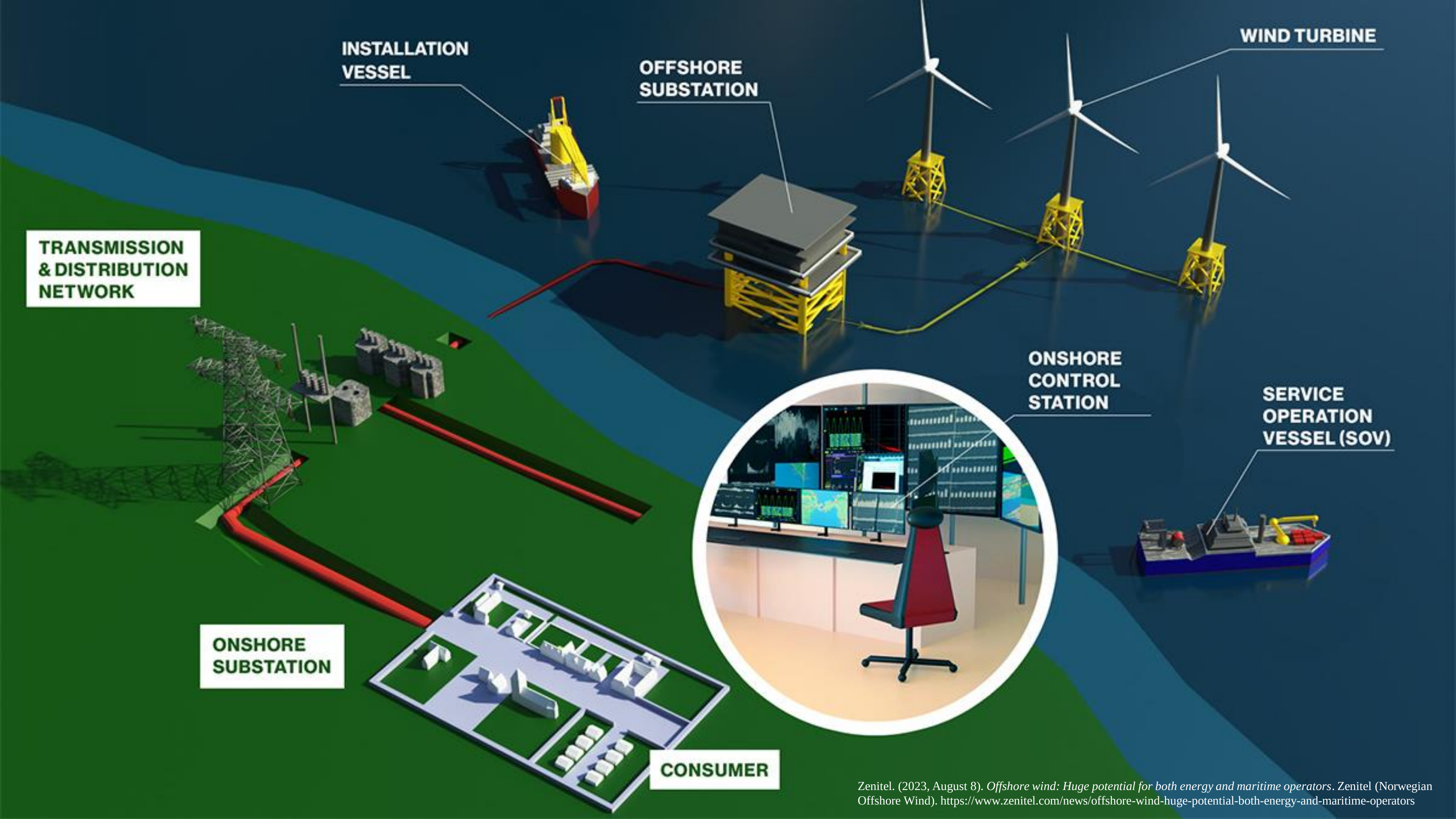


Thor offshore wind farm (800MW-1000MW) established in the North Sea, West of Nissum Fjord, ~20km from shore of Thorsminde town. [Source]

Utrecht University

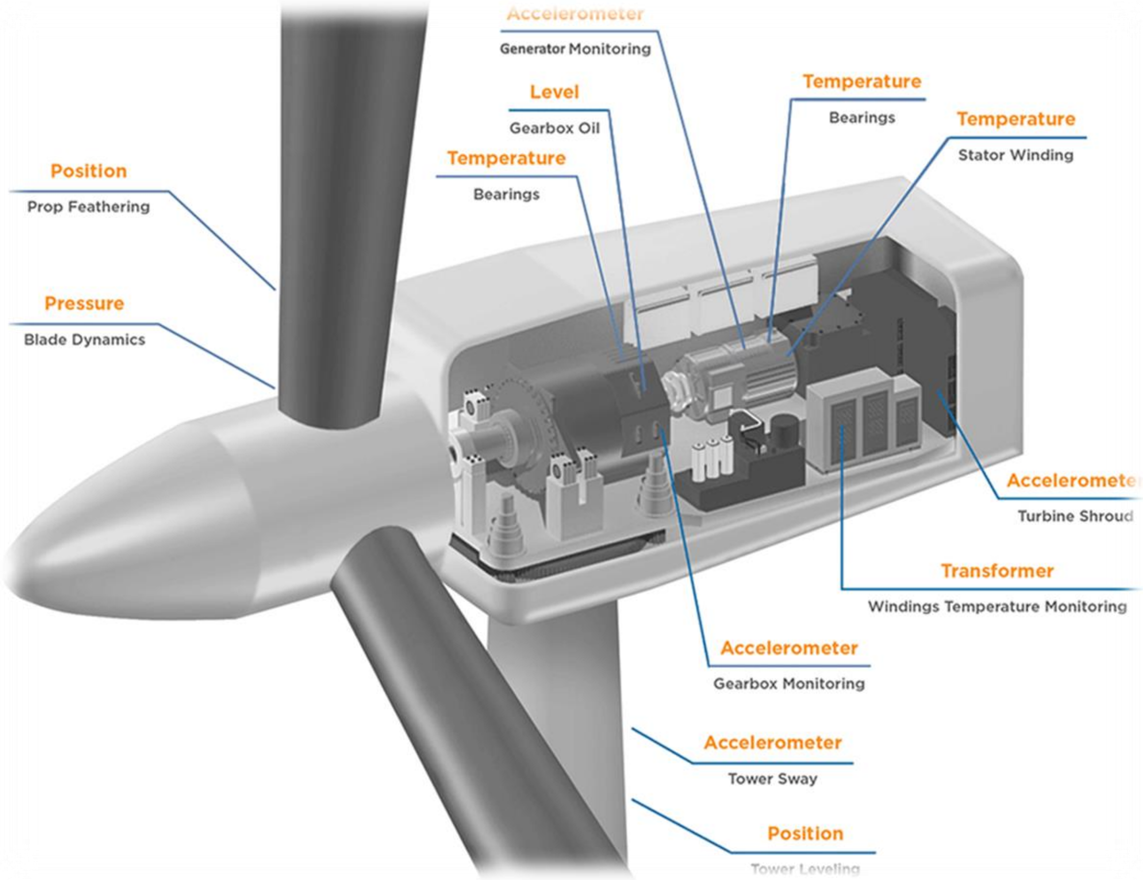
a) Mwangi, A. W. (2023). *Horizon 2020: IoT Data Acquisition System Design Method* (Deliverable No. D1.2, Version 2.0, Project InnoCyPES). European Commission. Peer-reviewed by G. Yang, M. Gibescu, E. Fumagalli, M. Gryning, & F. Martin. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5f9455af8&appId=PPGMS

b) Mwangi, Agrippina, Rishikesh Sahay, Elena Fumagalli, Mikkel Gryning, and Madeleine Gibescu. 2024. "*Towards a Software-Defined Industrial IoT-Edge Network for Next-Generation Offshore Wind Farms: State of the Art, Resilience, and Self-X Network and Service Management*" Energies 17, no. 12: 2897. https://doi.org/10.3390/en17122897



Zenitel. (2023, August 8). *Offshore wind: Huge potential for both energy and maritime operators*. Zenitel (Norwegian Offshore Wind). https://www.zenitel.com/news/offshore-wind-huge-potential-both-energy-and-maritime-operators

Data Acquisition Systems in Offshore Wind Farms ("Nerve Center")



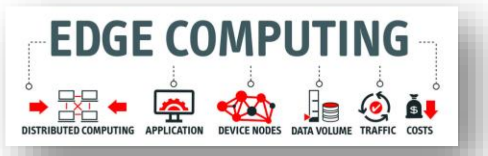
- The SCADA system are the "*nerve center*" for large-scale offshore wind farms, collecting data from wind turbine generators, digital substation components, and meteorological stations.
- These systems are vital for overseeing and controlling wind farm operations, offering comprehensive monitoring, control, and reporting functions. They accurately log events, improving the precision of alarm and event records, and reducing troubleshooting time.
- Offshore wind farm developers and operators usually procure SCADA systems from wind turbine manufacturers, who also double as SCADA suppliers.

a) Marti-Puig, P.; Blanco-M, A.; Cárdenas, J.J.; Cusidó, J.; Solé-Casals, J. Feature Selection Algorithms for Wind Turbine Failure Prediction. *Energies* **2019**, *12*, 453. https://doi.org/10.3390/en12030453
b) Mwangi, A. W. (2023). *Horizon 2020: IoT Data Acquisition System Design Method* (Deliverable No. D1.2, Version 2.0, Project InnoCyPES). European Commission. Peer-reviewed by G. Yang, M. Gibescu, E. Fumagalli, M. Gryning, & F. Martin. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5f9455af8&appId=PPGMS

Leveraging Industrial 4.0 technologies in next-generation data acquisition systems

"Embracing the digital era, the energy sector is undergoing a significant transformation that will see next-generation offshore wind farms leverage the power of technologies from the fourth industrial revolution (Industry 4.0) such as Industrial Internet of Things (IIoT), edge computing, and programmable networks to improve their data-acquisition systems." (Mwangi et al., 2024)

Monitor and manage offshore assets with unprecedented precision.



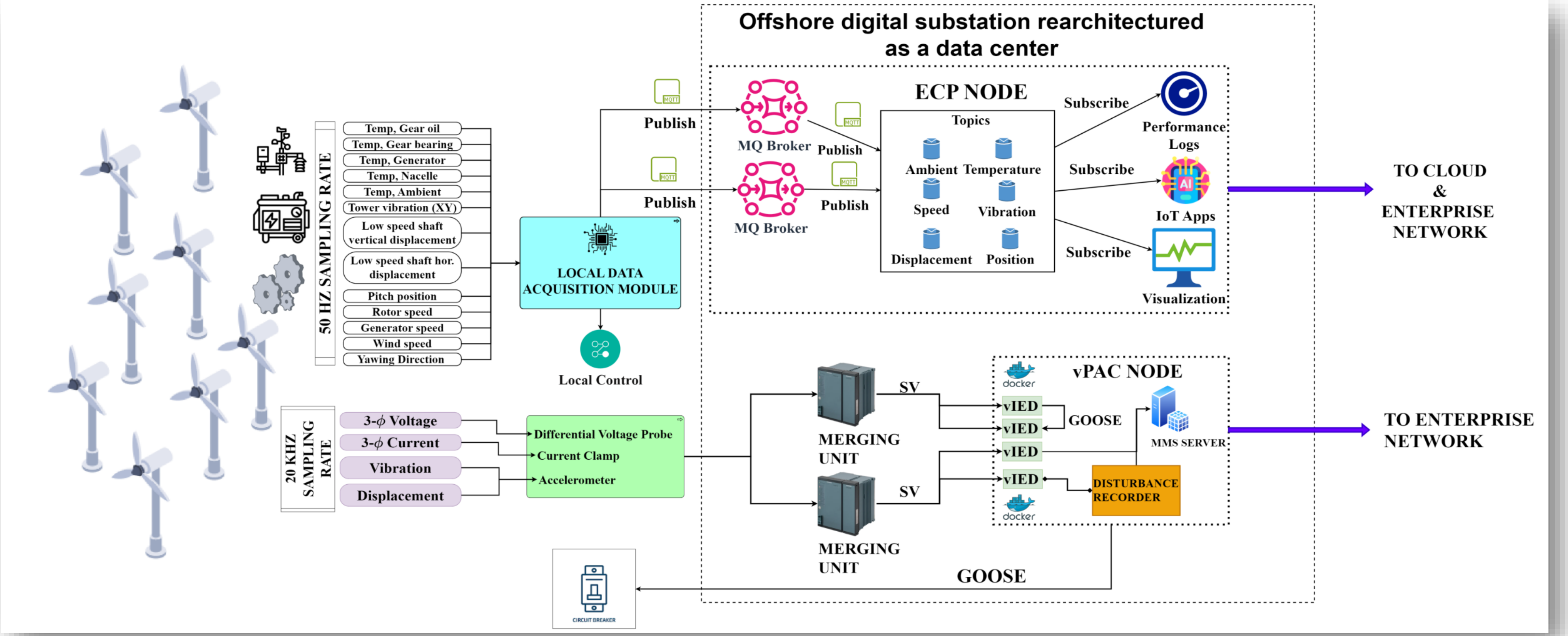
Process big data generated by IIoT devices closer to the offshore assets reducing dependency on distant data centers

Virtualization creates virtual instances of physical assets enabling swift deployment, scalability, and management.

Software-defined networks where network engineers can modify the behavior of the network using programming interfaces.

a) Mwangi, Agrippina, Rishikesh Sahay, Elena Fumagalli, Mikkel Gryning, and Madeleine Gibescu. 2024. "*Towards a Software-Defined Industrial IoT-Edge Network for Next-Generation Offshore Wind Farms: State of the Art, Resilience, and Self-X Network and Service Management*" Energies 17, no. 12: 2897. https://doi.org/10.3390/en17122897

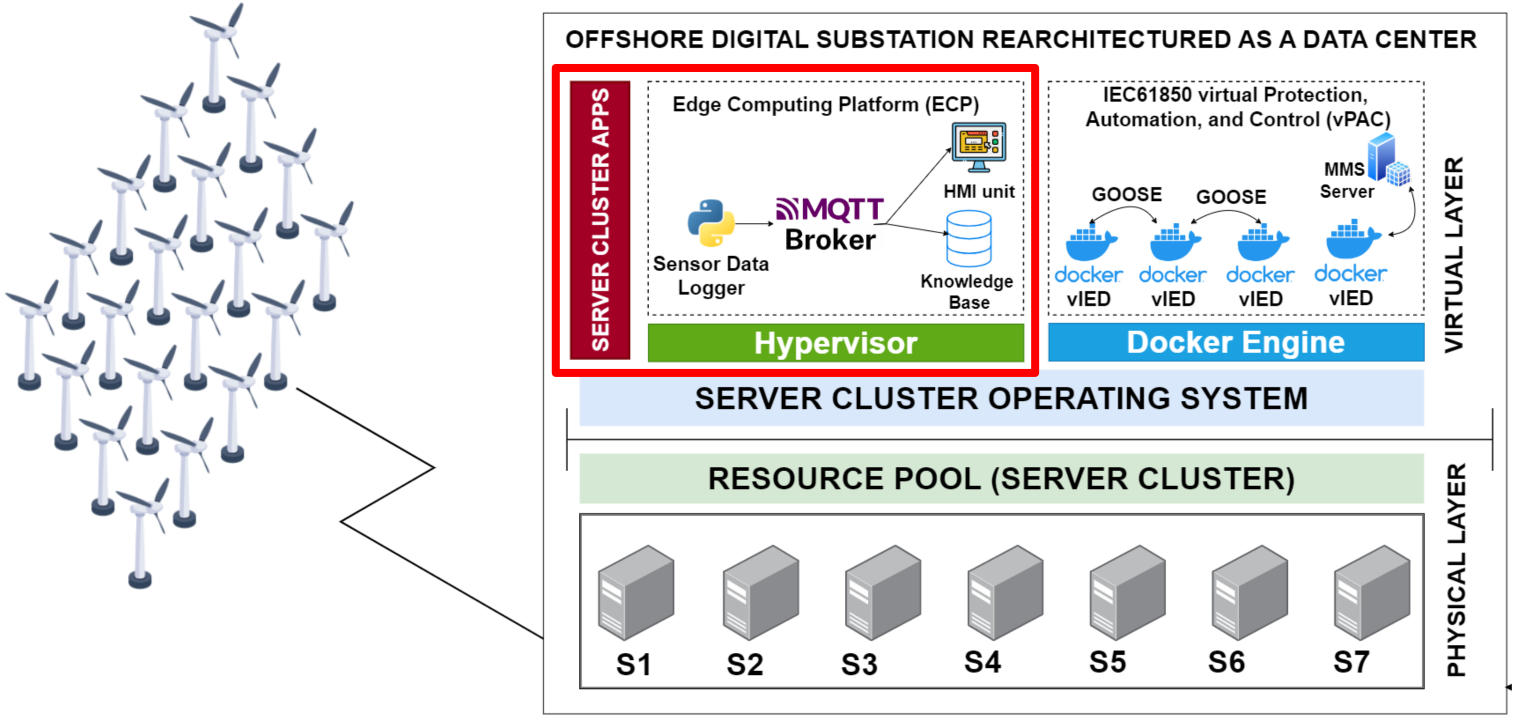
Next-generation data acquisition systems in offshore wind farms
(Industrial Internet of Things - IIoT)



Utrecht University

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

Next-generation data acquisition systems in offshore wind farms
(Edge computing platform for Industrial IoT)



Choosing an edge computing platform over the traditional IoT-to-cloud model reduces data transmission latency, enhances data security, and enables real-time decision making.

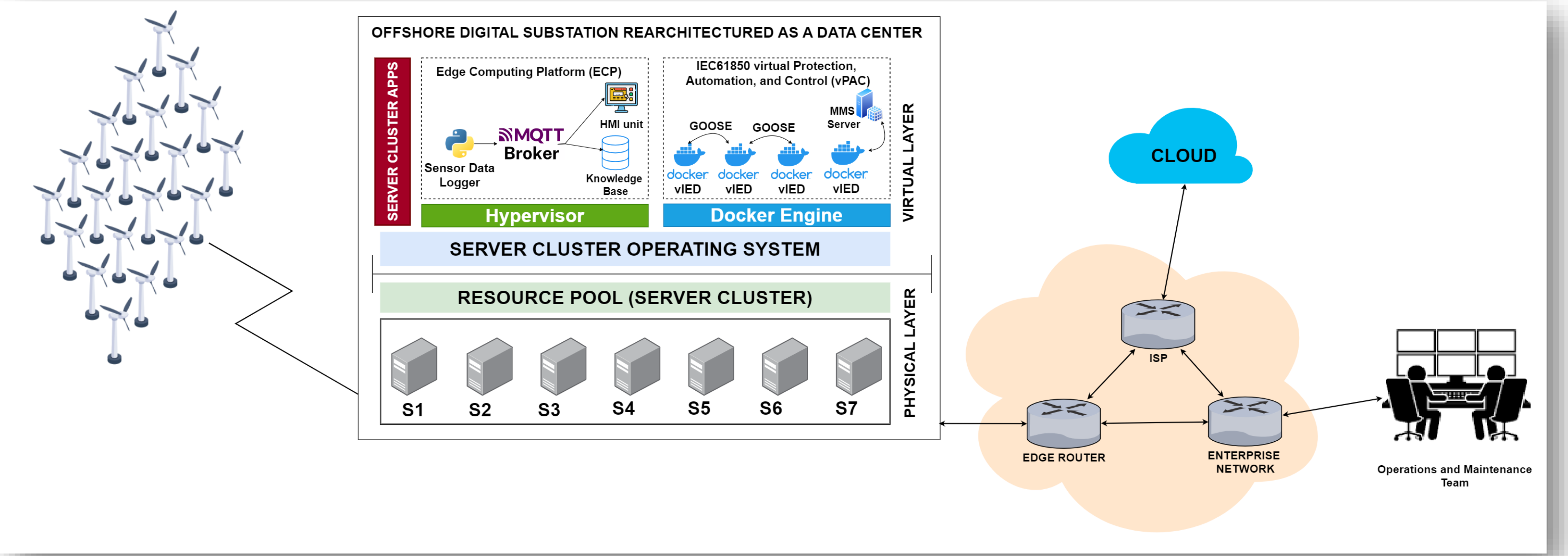
Utrecht University

Building resilient communication networks for next-generation offshore data acquisition systems

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

"Orchestration of these Industry 4.0 technologies hinges on resilient communication networks."

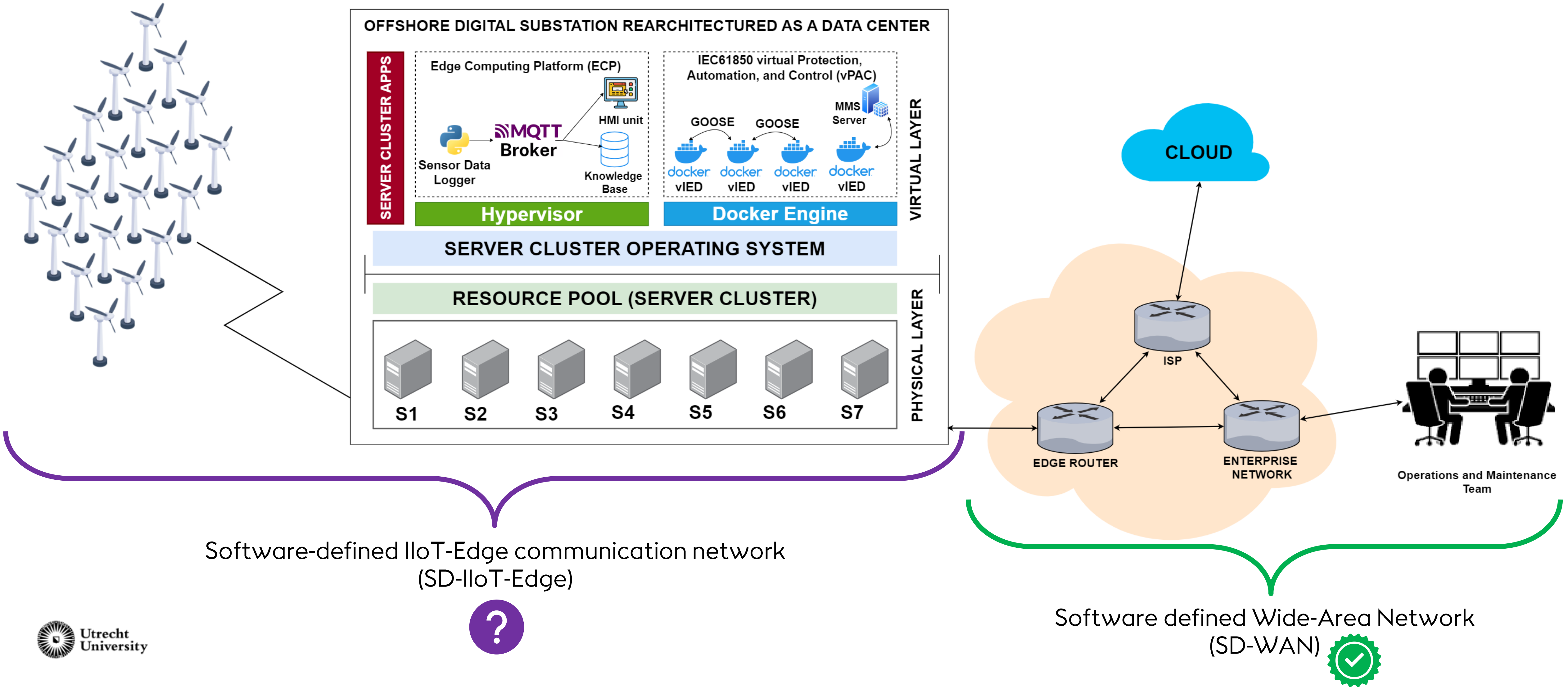
This research designs and validates software-defined communication networks capable of meeting the stringent performance requirements for efficient coordination of offshore wind farm services.



Utrecht University

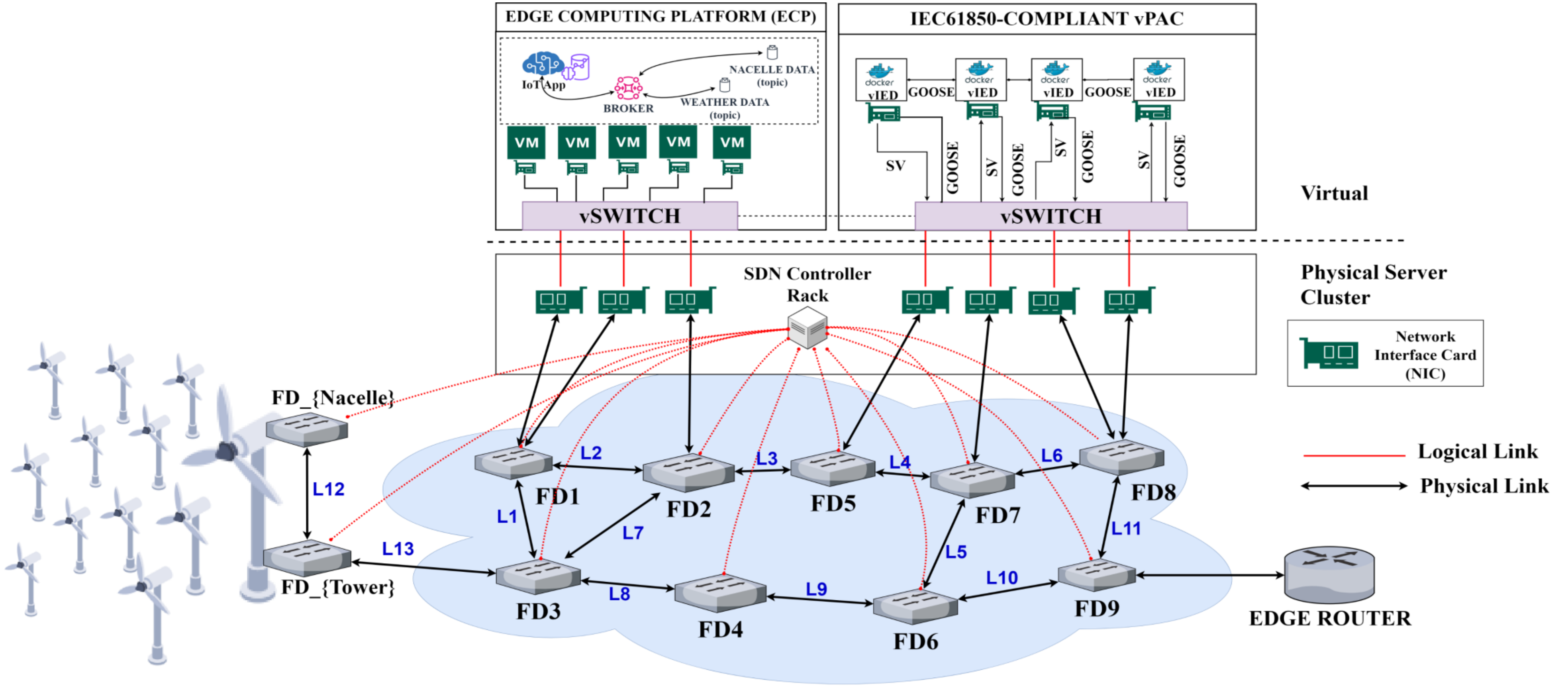
Building resilient communication networks for next-generation offshore data acquisition systems

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems



Software-defined Industrial IoT-Edge communication networks (SD-IIoT-Edge)

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems



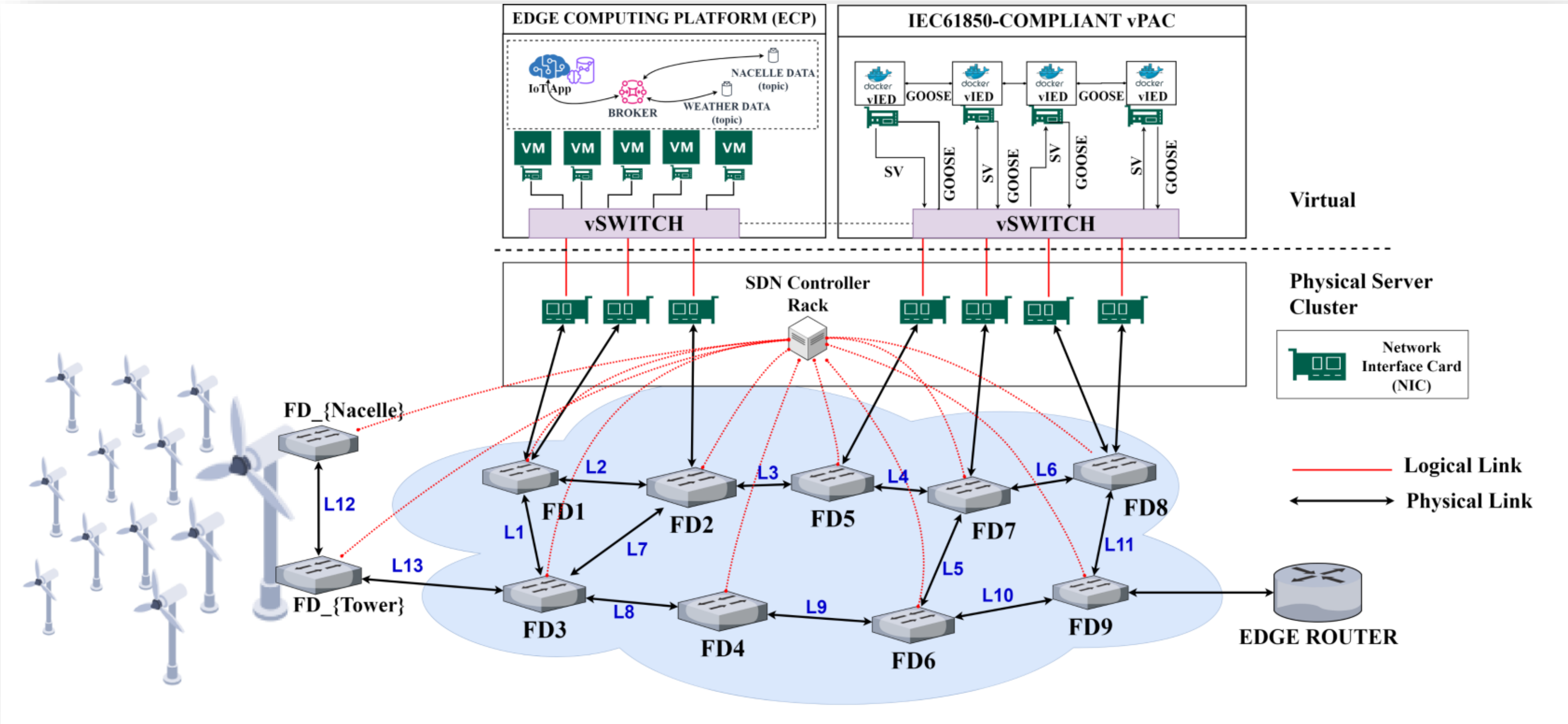
An out-of-band control SDN-Enabled IIoT-Edge network schematic illustrating the fiber-optic-based connectivity between a fleet of wind turbine generator nacelle and tower switches connected to the offshore hub's data center switches FD{1,...,9} leading to the server cluster's physical network interfaces and virtualized networks within the ECP and vPAC nodes.

Utrecht University

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

Software-defined Industrial IoT-Edge communication networks:
(Challenges and mitigation strategies)

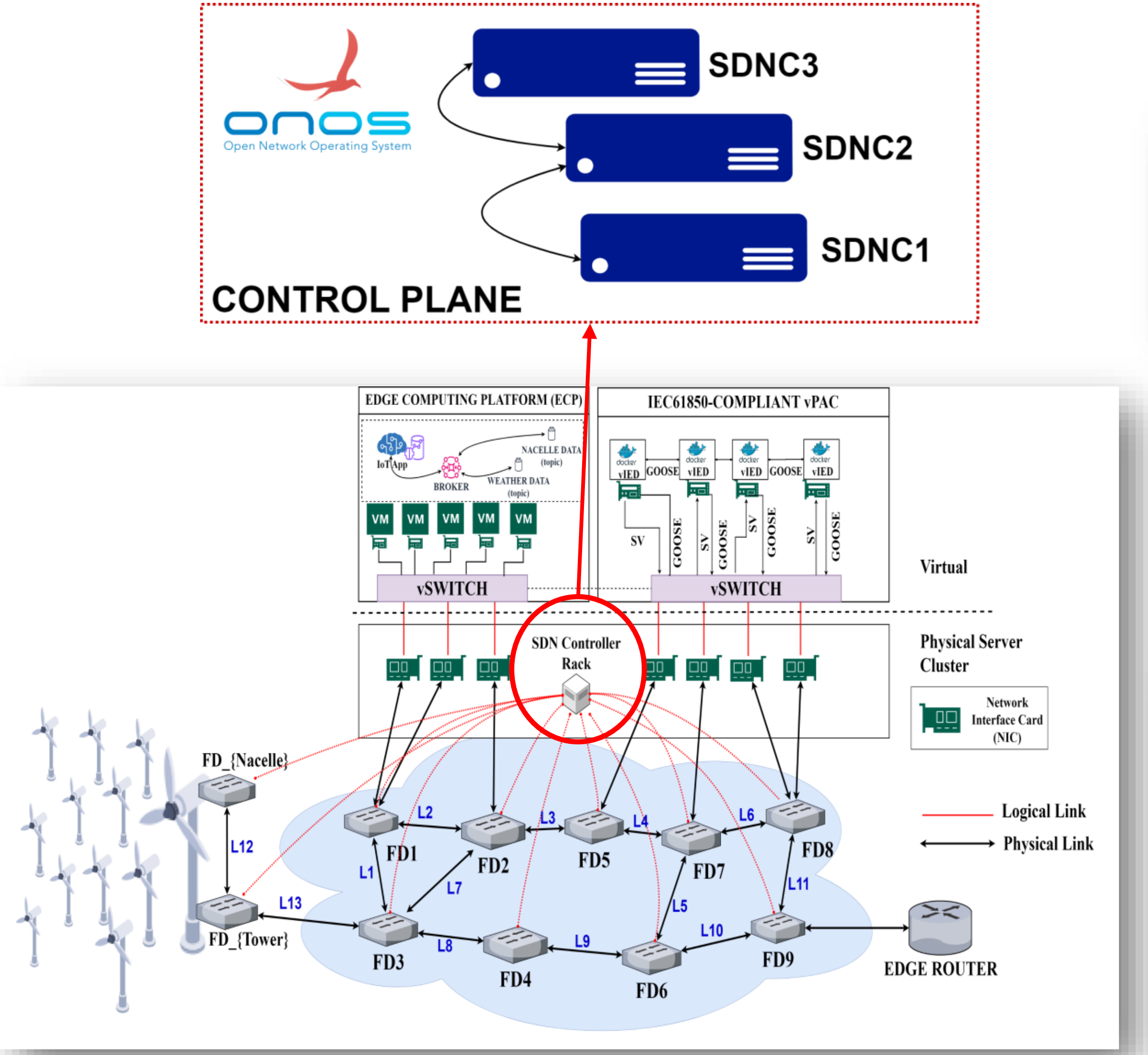
While SDN/NFV architectures have demonstrated significant value in many application scenarios, there remains scalability, performance, reliability, and security concerns that hinder their implementation in mission critical applications such as offshore wind farms.



1 { • Scalability
2 { • Performance
3 { • Reliability
4 { • Security

Utrecht University

Scalability in software-defined IIoT-Edge communication networks




```
In [1]: runfile('C:/Users/amwangi254/JP3/ApplicationPlane/network_monitoring_module.py',
wdir='C:/Users/amwangi254/JP3/ApplicationPlane')
Enter the IP address of the ONOS controller (default is 192.168.0.7): 192.168.0.7
Enter the username for ONOS controller (default is 'onos'): onos
Enter the password for ONOS controller (default is 'rocks'): rocks
Data has been written to 'port_stats.csv'.
```

- SDN Clusters guarantee redundancy by deploying (n+1) SDN controller to manage the software-defined network. It is recommended to have a minimum of 3 SDN controllers for every network.
- Running the raft algorithm to assign leadership roles in the SDN controller cluster.

```
07:25:35.139 INFO  [atomix-0] Started
07:25:35.208 INFO  [atomix-0] Starting server for partition PartitionId{id=1, group=system}
07:25:35.538 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1} - Transitioning to FOLLOWER
07:25:38.446 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1} - Transitioning to CANDIDATE
07:25:38.448 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1}{role=CANDIDATE} - Starting election
07:25:38.461 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1} - Transitioning to LEADER
07:25:38.469 INFO  [raft-server-system-partition-1] RaftServer{system-partition-1} - Found leader 192.168.0.6
07:25:39.147 INFO  [raft-partition-group-system-0] Started
07:25:39.310 INFO  [raft-partition-group-system-0] Starting server for partition PartitionId{id=1, group=raft}
07:25:39.435 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1} - Transitioning to FOLLOWER
07:25:42.042 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1} - Transitioning to CANDIDATE
07:25:42.043 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1}{role=CANDIDATE} - Starting election
07:25:42.061 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1} - Transitioning to LEADER
07:25:42.062 INFO  [raft-server-raft-partition-1] RaftServer{raft-partition-1} - Found leader 192.168.0.6
07:25:42.921 INFO  [raft-partition-group-raft-3] Started
07:25:42.921 INFO  [raft-partition-group-raft-3] Started
07:25:43.087 INFO  [raft-partition-group-system-2] Started
07:25:43.089 INFO  [raft-partition-group-system-2] Started
07:25:43.090 INFO  [SCR Component Actor] Started
07:25:43.093 INFO  [FelixStartLevel] Updated node 192.168.0.6 state to ACTIVE
07:25:43.096 INFO  [FelixStartLevel] Started
```

Performance in software-defined IIoT-Edge communication networks

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

- It is important for the software-defined IIoT-Edge network to meet the performance requirements for the different data traffic types.
- These data traffic types are categorized into:
  - Critical, time-sensitive data traffic (protection, control, analogue measurements, status information, and data polling WPP services).
  - Best-effort data traffic (reporting and logging, video surveillance, and wireless network connectivity for O&M personnel).

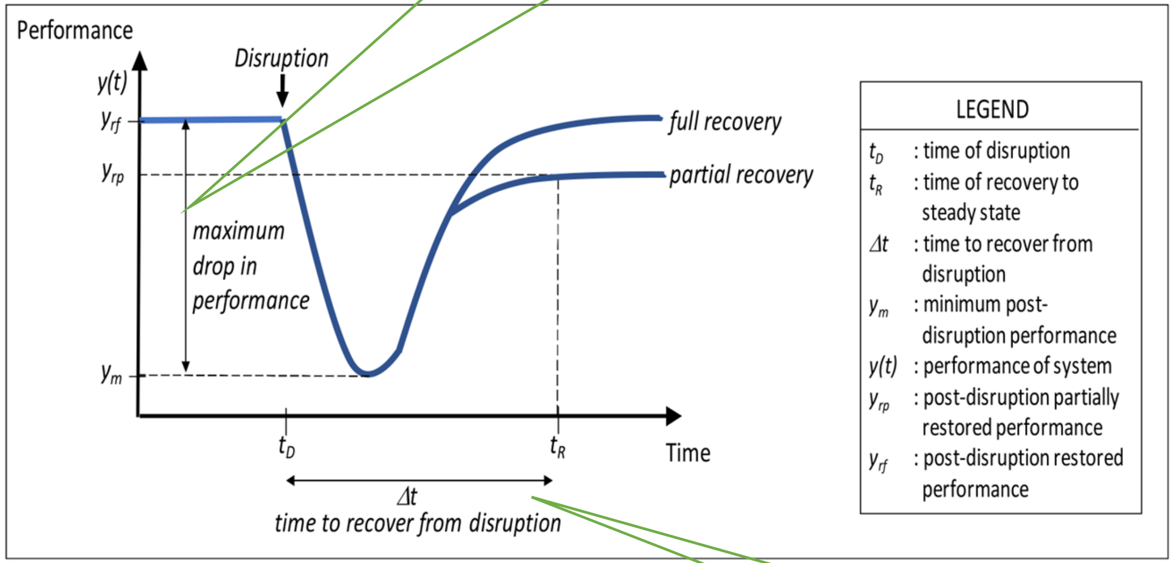
Service	Communication Direction	Priority	Data Rate	Latency	Reliability	Packet Loss Rate
Protection traffic	WTG → vPAC	1	76,816 bytes/s	4 ms	99.999%	$<10^{-9}$
Analogue measurements	WTG → vPAC/ECP	2	225,544 bytes/s	16 ms	99.999%	$<10^{-6}$
Status information	WTG → ECP	2	58 bytes/s	16 ms	99.999%	$<10^{-6}$
Reporting and logging	WTG → ECP	3	15 KB every 10 min	1 s	99.999%	$<10^{-6}$
Video surveillance	WTG → ECP	4	250 kb/s–1.5 Mb/s	1 s	99%	No specific requirement
Control traffic	vPAC → WTG	1	20 kbs/per turbine	16 ms	99.999%	$<10^{-9}$
Data polling	ECP/vPAC → WTG	2	2 KB every second	16 ms	99.999%	$<10^{-6}$
Internet connection	Internet → WTG/ECP/vPAC	3	1 GB every two months	60 min	99%	No specific requirement

Offshore wind farm data communication parameters between the wind turbine generators (WTG), the offshore hub-mounted data center components, and the Internet.

Performance in software-defined IIoT-Edge communication networks

Innovative Tools for Cyber-Physical Energy Systems

Minimize the maximum drop in performance



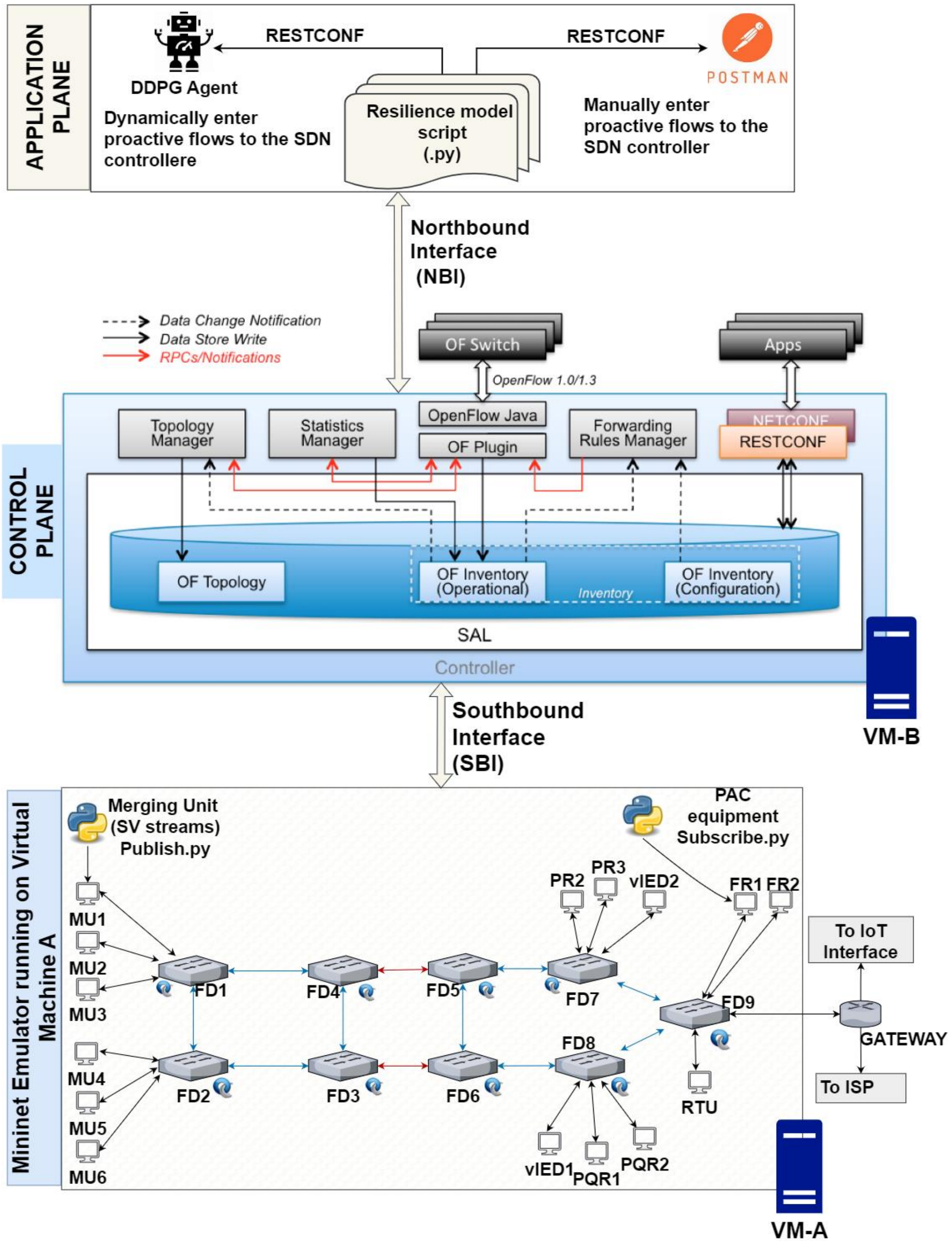
Minimize the time to recovery

- ❑ Like any other communication network, the proposed SDN-enabled IIoT-Edge network is susceptible to stochastic failures (random component failure, software glitches, resource fluctuation, etc.) that disrupt service.
- ❑ Offshore wind farms transmit critical, latency-sensitive data samples through the proposed network hence we must guarantee resilience in the proposed network.
- ❑ Objective:
  - ❑ Investigate the dependability of the proposed network
  - ❑ Build resilience using RL approaches for zero-touch networks (proactive network automation trends)

Utrecht University

System Methodology

- Developed a simulation testbed in collaboration with the TU Delft Control Room of the Future (CRoF) team.
- Using Mininet to simulate the proposed SDN-enabled IIoT-Edge network (running scripts to mimic the critical, latency-sensitive data samples).
- Using OpenDayLight SDN control with a flat distributed architecture for workload balancing (flow management).
- Using DDPG to design the resilience model that proactively manages the network to guarantee swift response to stochastic failures.



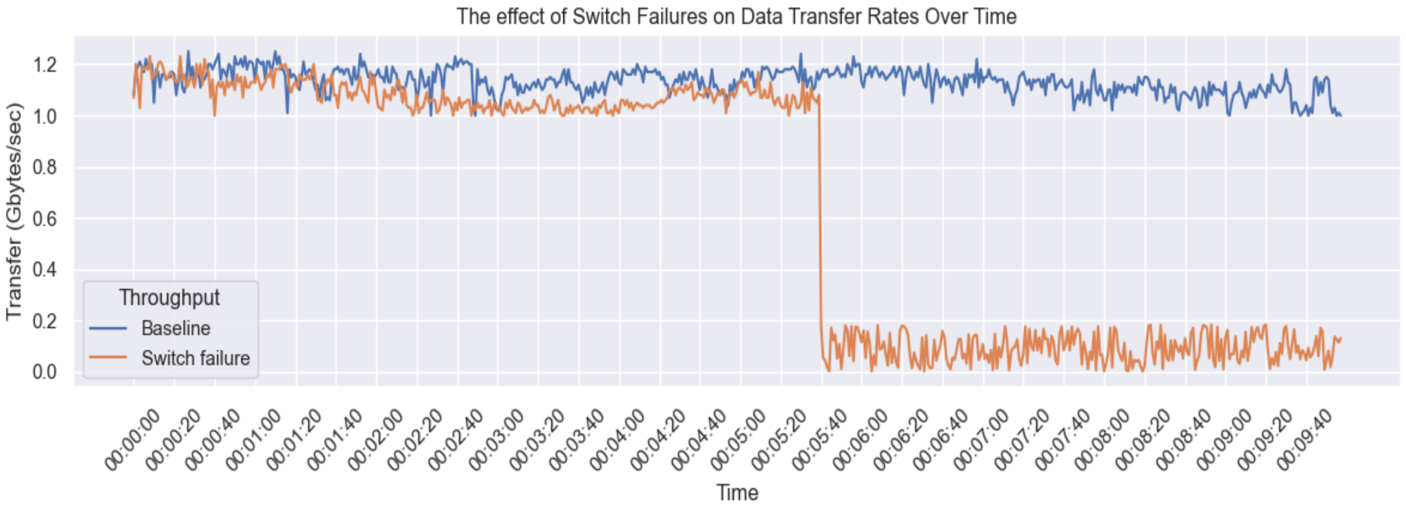
Utrecht University

TU Delft Delft University of Technology

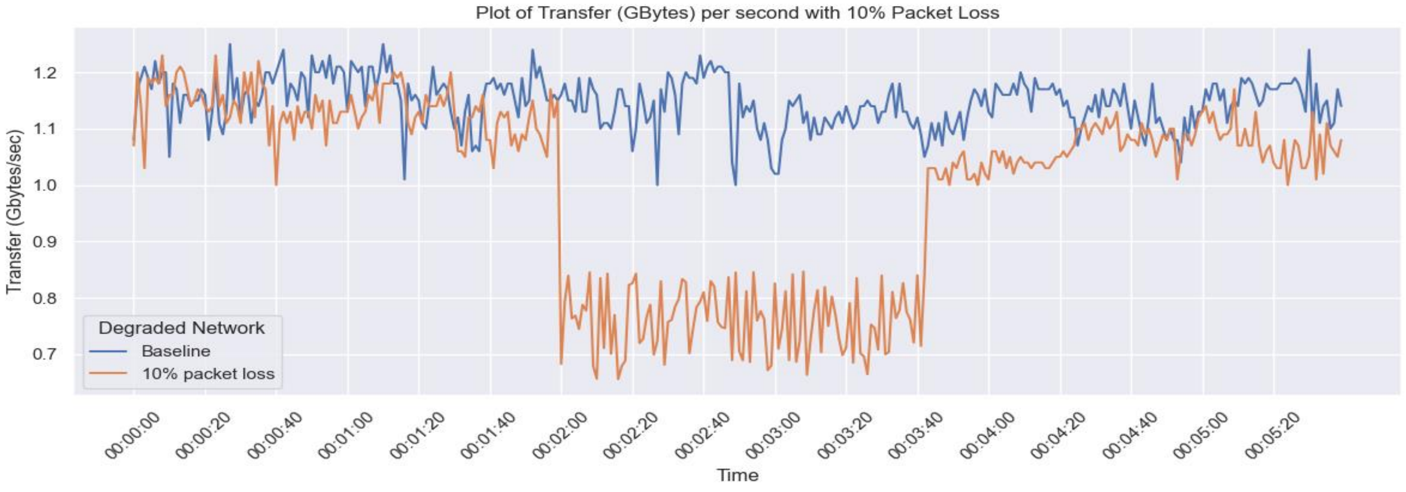
Performance in software-defined IIoT-Edge communication networks

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

- The plot shows the effect of switch failures on data transfer rates over time, where the baseline throughput remains stable, but a switch failure causes a significant drop in the transfer rate, leading to lower, fluctuating performance thereafter.



- The plot illustrates the impact of 10% packet loss on data transfer rates over time, where the baseline shows stable performance, while the network with packet loss experiences reduced and more erratic transfer rates.

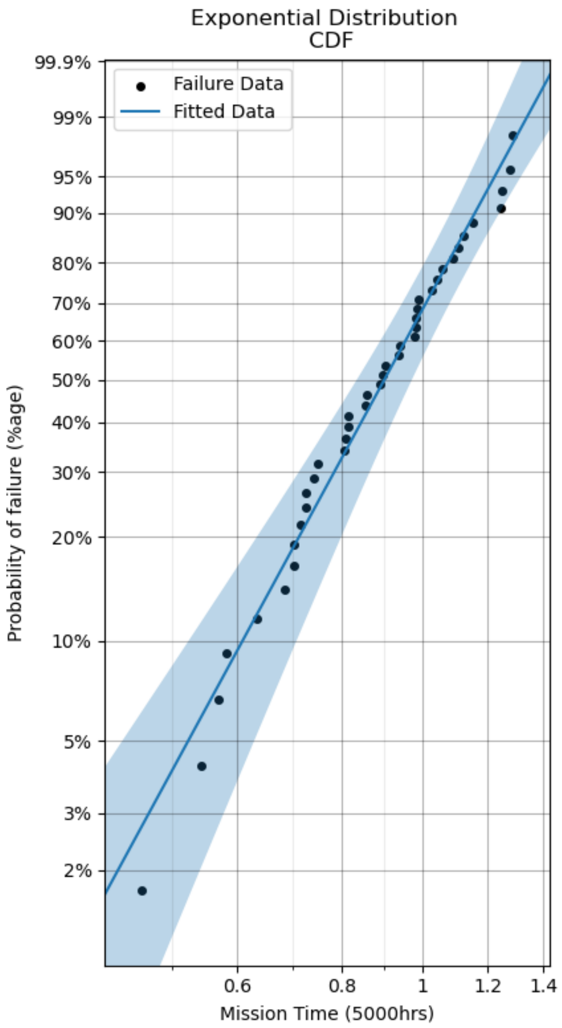


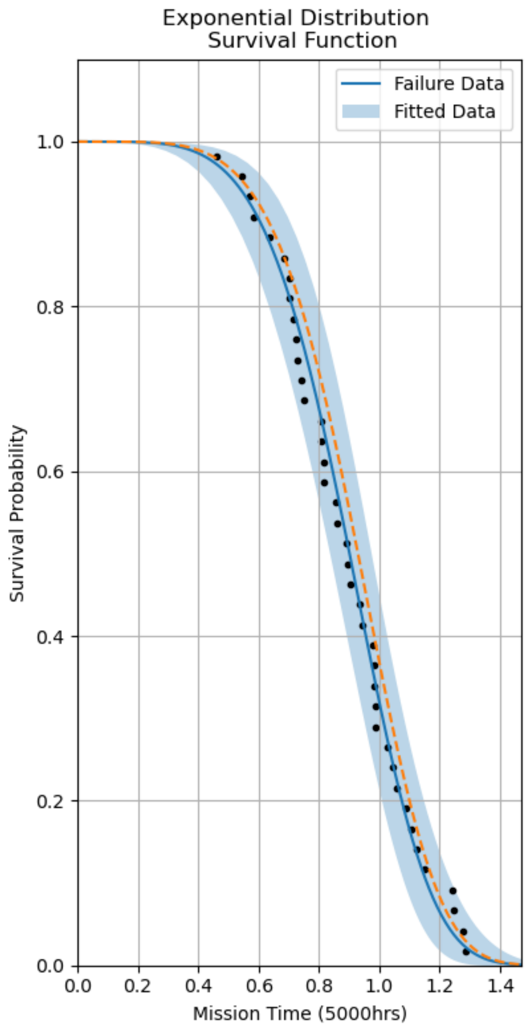
Utrecht University

Reliability in software-defined IIoT-Edge communication networks

InnoCyPES
Innovative Tools for Cyber-Physical Energy Systems

- The reliability of the software-defined IIoT–Edge network addresses architectural robustness, failover mechanisms, and performance under stress conditions.
- Given that these networks are deployed in extreme environments with unpredictable weather, there is a need to deploy ruggedized equipment that can withstand the harsh conditions of the offshore environment.
- The network reliability and availability are constantly affected, and, as a result, more advanced fast failover recovery methods are studied to tackle the availability issues by defining reliability or failure models and making inferences from the model results to determine the availability.





Utrecht University

Value creation

Software-defined Intent-based IoT Networks

Higher granularity of data

Cost-effective, flexible and scalable IoT networks

Efficient resource utilization

Rapid service rollout

Resources

1) **Mwangi, Agrippina,** N.Kabbara, P. Coudray, M. Gryning, and M. Gibescu, "Investigating the dependability of software-defined IIoT-Edge networks in next-generation offshore wind farms", IEEE Transactions on Network and Service Management, 2024. https://doi.org/10.1109/TNSM.2024.3458447

2) **Mwangi, Agrippina**, Rishikesh Sahay, Elena Fumagalli, Mikkel Gryning, and Madeleine Gibescu. 2024. "Towards a Software-Defined Industrial IoT-Edge Network for Next-Generation Offshore Wind Farms: State of the Art, Resilience, and Self-X Network and Service Management" Energies 17, no. 12: 2897. https://doi.org/10.3390/en17122897

3) **Mwangi, A.,** Fumagalli, E., Gryning, M., & Gibescu, M. (2023, October). Building Resilience for SDN-Enabled IoT Networks in Offshore Renewable Energy Supply. In 2023 IEEE 9th World Forum on Internet of Things (WF-IoT) (pp. 1-2). IEEE. https://doi.org/10.1109/WF-IoT58464.2023.10539483

4) **Mwangi, A.,** Sundsgaard, K., Vilaplana, J. A. L., Vilerá, K. V., & Yang, G. (2023, June). A system-based framework for optimal sensor placement in smart grids. In 2023 IEEE Belgrade PowerTech (pp. 1-6). IEEE. https://doi.org/10.1109/PowerTech55446.2023.10202987

Ms Azure Proof-of-Concept Testbed Design for the European Telecommunication Standards Institute (ETSI) self-healing framework
(Github Repository)

Utrecht University

Sharing science,
shaping tomorrow

Our Partners:

Ørsted

EDF

TU Delft