# Study Committee C1

## Power System Development and Economics

## Paper 10557_2022

# Technical Feasibility Study of Bornholm Energy Island Transmission System

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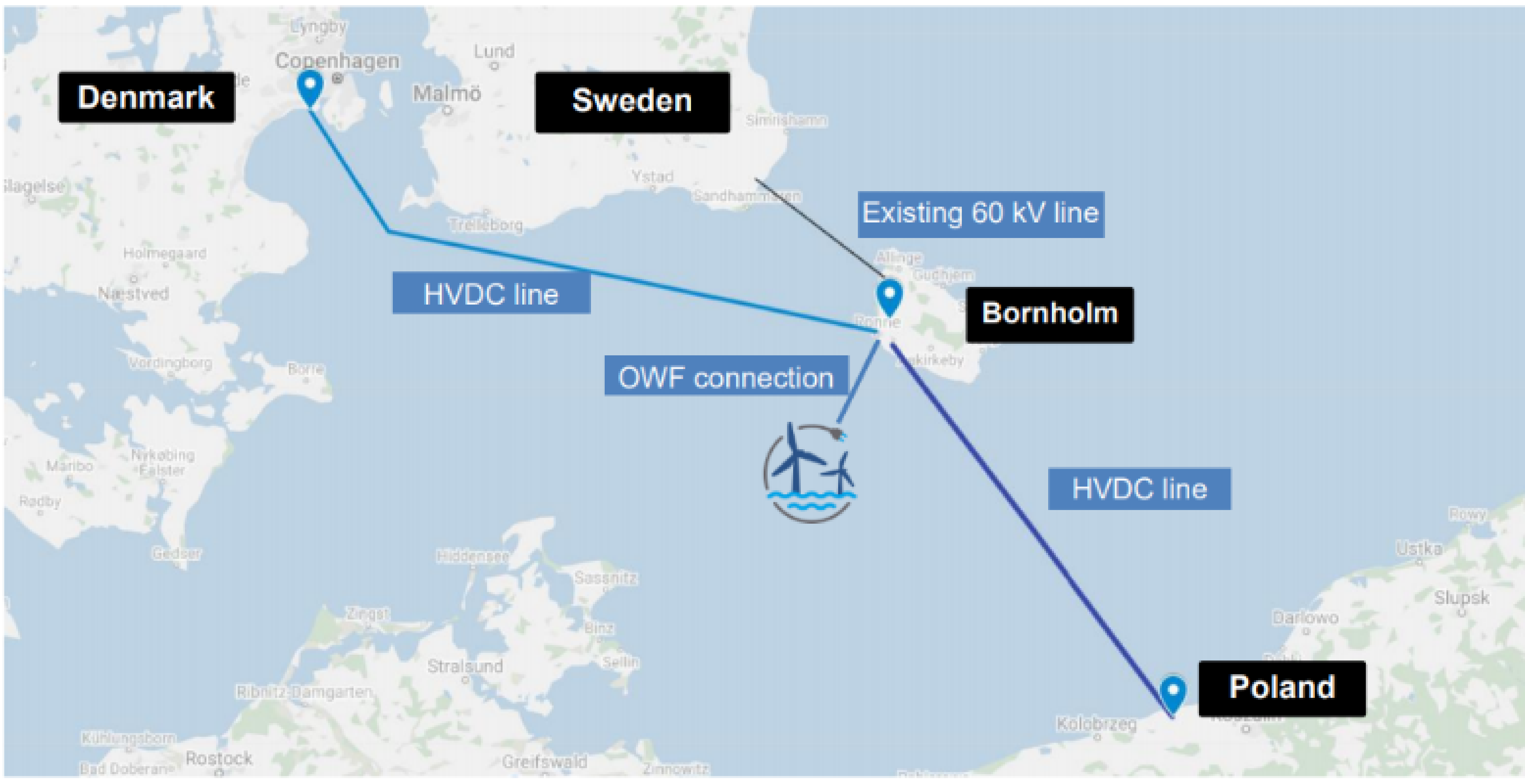
## Motivation

- Energy islands are a promising solution for future large scale deployment of renewable energy technologies, particularly offshore wind, combined with power transmission between countries as well as other energy technologies
- To avoid typical risks and hurdles related to offshore applications, why not start from a natural island? The Danish island of Bornholm was identified as a candidate for such an application, with a large amount of planned offshore wind and the potential to be combined with transmission between countries (DK-PL in this study, DK-DE as a first step in reality)
- What transmission solutions should one use to deliver this project?




## Case study conception

Wind power development
Interconnection capacity between countries
Build-out sequence

<table>
<tr><th rowspan="2"></th><th rowspan="2">Scen.</th><th colspan="2">Total offshore wind generation Bornholm [GW]</th><th colspan="2">Total transmission capacity Bornholm – DK [GW]</th><th colspan="2">Total transmission capacity Bornholm – Poland [GW]</th></tr>
<tr><th>2026</th><th>2028</th><th>2026</th><th>2028</th><th>2026</th><th>2028</th></tr>
<tr><td rowspan="3">Not all energy can be sent to DK</td><td>1a</td><td rowspan="6">2</td><td rowspan="6">3</td><td>1.5</td><td>1.5</td><td>1.5</td><td>1.5</td></tr>
<tr><td>1b</td><td>2.1</td><td>2.1</td><td>2.1</td><td>2.1</td></tr>
<tr><td>1c</td><td>1.4</td><td>2.4</td><td>0.6</td><td>0.6</td></tr>
<tr><td rowspan="3">All energy can be sent to DK</td><td>2a</td><td>2</td><td>3</td><td>0.6</td><td>0.6</td></tr>
<tr><td>2b</td><td>2.6</td><td>3.6</td><td>0.6</td><td>0.6</td></tr>
<tr><td>2c</td><td>2</td><td>3</td><td>0.6</td><td>1.2</td></tr>
</table>

DC hub configurations
Max loss of infeed (LoI) limits
HVDC voltages and configuration
Wind farm capacity
Electricity prices
Metallic return costs

42000+ cases

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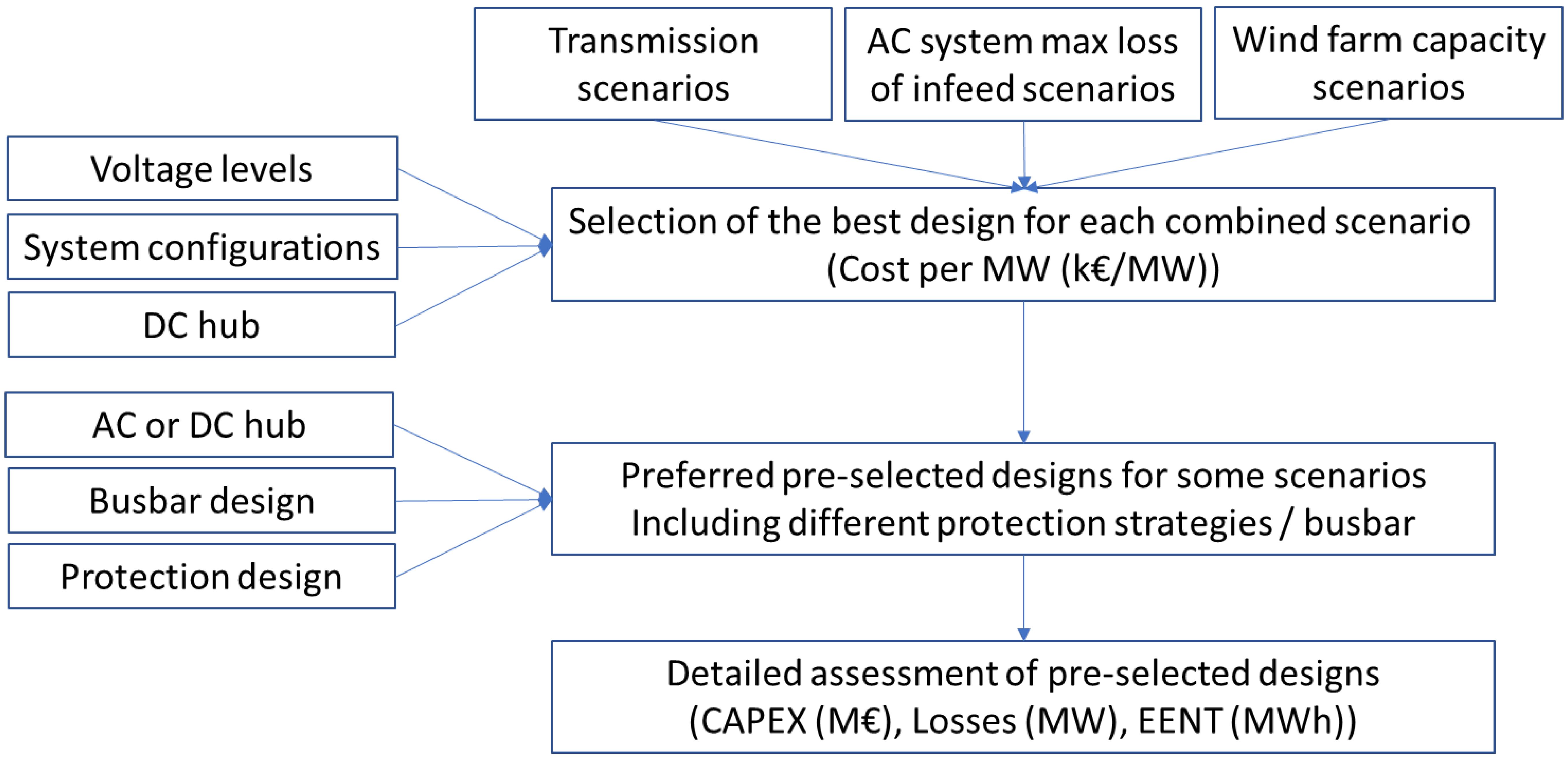
# Technical Feasibility Study of Bornholm Energy Island Transmission System continued

## Method/Approach

- A technoeconomic feasibility study was performed
- Initially, project CAPEX (capital expenditure) was analyzed
- EENT (Expected Energy Not Transmitted) was analyzed (but not monetized) for different Bornholm hub configurations and protection strategies




$$cost\ per\ MW = \frac{Total\ project\ costs}{Power(DK \leftrightarrow BH) + Power(BH \leftrightarrow PL) + Wind\ farm\ generation}$$

## Results – CAPEX only

- With basic LoI limit, all solutions are 320kV (600MW blocks are more CAPEX efficient at 320kV)
- For larger LoI limits, some 400kV solutions start to appear
- Scenario 1a, due to low needed flexibility, results in monopole
- Bipoles appear superior for more complex scenarios
- Increasing LoI limits can, for the same scenario, decrease CAPEX, though not in a linear manner

| Maximum allowed LoI [MW] | Scenario | CAPEX [k€/MW] | Total CAPEX [M€] | Configuration | | | |
|---|---|---|---|---|---|---|---|
| | | | | Voltage [kV] | DK-BH | BH-PL | OWF |
| 600 | 1a | 284 | 1706 | 320 | S-MP | S-MP | S-MP |
| | 1b | 239 | 1718 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 1c | 295 | 1768 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2a | 290 | 1913 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2b | 313 | 2253 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2c | 299 | 2154 | 320 | BP-CMR | BP-CMR | BP-CMR |
| 750 | 1a | 229 | 1374 | 400 | BP-MR | BP-MR | BP-MR |
| | 1b | 239 | 1718 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 1c | 273 | 1639 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2a | 290 | 1913 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2b | 279 | 1977 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2c | 299 | 2154 | 320 | BP-CMR | BP-CMR | BP-CMR |
| 900 | 1a | 229 | 1374 | 400 | BP-MR | BP-MR | BP-MR |
| | 1b | 239 | 1718 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 1c | 273 | 1639 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2a | 290 | 1913 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2b | 279 | 1977 | 320 | BP-CMR | BP-CMR | BP-CMR |
| | 2c | 299 | 2154 | 320 | BP-CMR | BP-CMR | BP-CMR |

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## Results – EENT

Selected scenarios:
1a, 750MW LoI, 400kV
1b, 600MW LoI, 320kV
2a, 600MW LoI, 320kV
2b, 750MW LoI, 320kV

Options:
1)DC hub, fully selective, double busbar double breaker, hybrid DC breaker
2)DC hub, fully selective, double breaker double busbar, mechanical DC breaker
3)DC hub, non-selective, double busbar single breaker, mechanical DC breaker
4)DC hub, non-selective, double busbar single breaker, full-bridge MMC
5)State-of-art: AC hub with AC protection

- CAPEX (not depicted) is larger for options 1), 2) and 4) are more costly than 3), while 5) is the cheapest
- When employing DC breakers, CAPEX amounts to between 4% and 15%
- Transmission losses are approx. 5 times more relevant than EENT due to outages
- Expectedly, transmission losses are more relevant in option 5), more so when larger power exchange between countries happens
- Total contribution of protection strategy to EENT and losses is only 1-3%

## Discussion

- HVDC voltage level:
  - 320kV state-of-art and cost effective
  - But future trend seems to be for 525kV
- LoI limits:
  - Adjustment of LoI limits requires system wide analysis beyond scope
  - Coupling onshore stations with adjustable loads may help
- DC hub design
  - Bipole required to meet LoI limit
  - Common metallic return improves economics but needs to be accepted environmentally
  - Different busbar configurations to be looked at
- Stability
  - How to manage power during converter outage?
  - Loss of wind power, AC choppers, large DC choppers or oversized converters may be needed
- De-risking and interoperability
  - Interoperability and DC breaker TRL possible issues
  - Modular and flexible system (e.g. both AC and DC hub) may enable de-risking
  - Bornholm being a natural island has reduced risks


a1) Scenario 1a 750 MW loss of infeed, 400 kV EENT (MWh/h)

| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|---|---|---|---|---|---|
| Grid EENT | 17,61 | 17,61 | 17,60 | 17,60 | 23,94 |
| Both EENT | 0,27 | 0,27 | 0,29 | 0,29 | 0,00 |
| Protection EENT | 0,09 | 0,09 | 0,16 | 0,16 | 0,00 |

a2) Scenario 1a 600 MW loss of infeed, 320 kV Scenario 1a, 750 LoI (MWh/h)

| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|---|---|---|---|---|---|
| Inductor_Loss | 0,90 | 1,07 | 0,44 | 0,57 | 0,00 |
| Cable Loss | 14,68 | 14,68 | 14,68 | 14,85 | 14,63 |
| Transformer Loss | 10,48 | 10,48 | 10,48 | 10,48 | 12,55 |
| Converter Loss | 26,82 | 26,82 | 36,21 | 26,82 | 32,14 |

b1) Scenario 1b 600 MW loss of infeed, 320 kV EENT (MWh/h)

| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|---|---|---|---|---|---|
| Grid EENT | 7,56 | 7,56 | 7,55 | 7,55 | 10,86 |
| Both EENT | 0,13 | 0,13 | 0,14 | 0,14 | 0,00 |
| Protection EENT | 0,03 | 0,03 | 0,05 | 0,05 | 0,00 |

b2) Scenario 1b 600 MW loss of infeed, 320 kV Losses (MWh/h)

| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|---|---|---|---|---|---|
| Inductor_Loss | 0,88 | 1,00 | 0,66 | 0,64 | 0,00 |
| Cable Loss | 4,50 | 4,50 | 4,50 | 4,50 | 4,49 |
| Transformer Loss | 11,39 | 11,39 | 11,39 | 11,39 | 14,26 |
| Converter Loss | 29,14 | 29,14 | 39,33 | 29,14 | 36,50 |

c1) Scenario 2a 600 MW loss of infeed, 320 kV EENT (MWh/h)

| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|---|---|---|---|---|---|
| Grid EENT | 11,96 | 11,96 | 11,96 | 11,96 | 12,25 |
| Both EENT | 0,30 | 0,30 | 0,31 | 0,31 | 0,00 |
| Protection EENT | 0,07 | 0,07 | 0,12 | 0,12 | 0,00 |

c2) Scenario 2a 600 MW loss of infeed, 320 kV Losses (MWh/h)

| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|---|---|---|---|---|---|
| Inductor_Loss | 1,12 | 1,29 | 0,70 | 0,77 | 0,00 |
| Cable Loss | 10,55 | 10,55 | 10,55 | 10,55 | 10,52 |
| Transformer Loss | 9,16 | 9,16 | 9,16 | 9,16 | 9,90 |
| Converter Loss | 23,42 | 23,42 | 31,62 | 23,42 | 25,32 |

d1) Scenario 2b 750 MW loss of infeed, 320 kV EENT (MWh/h)

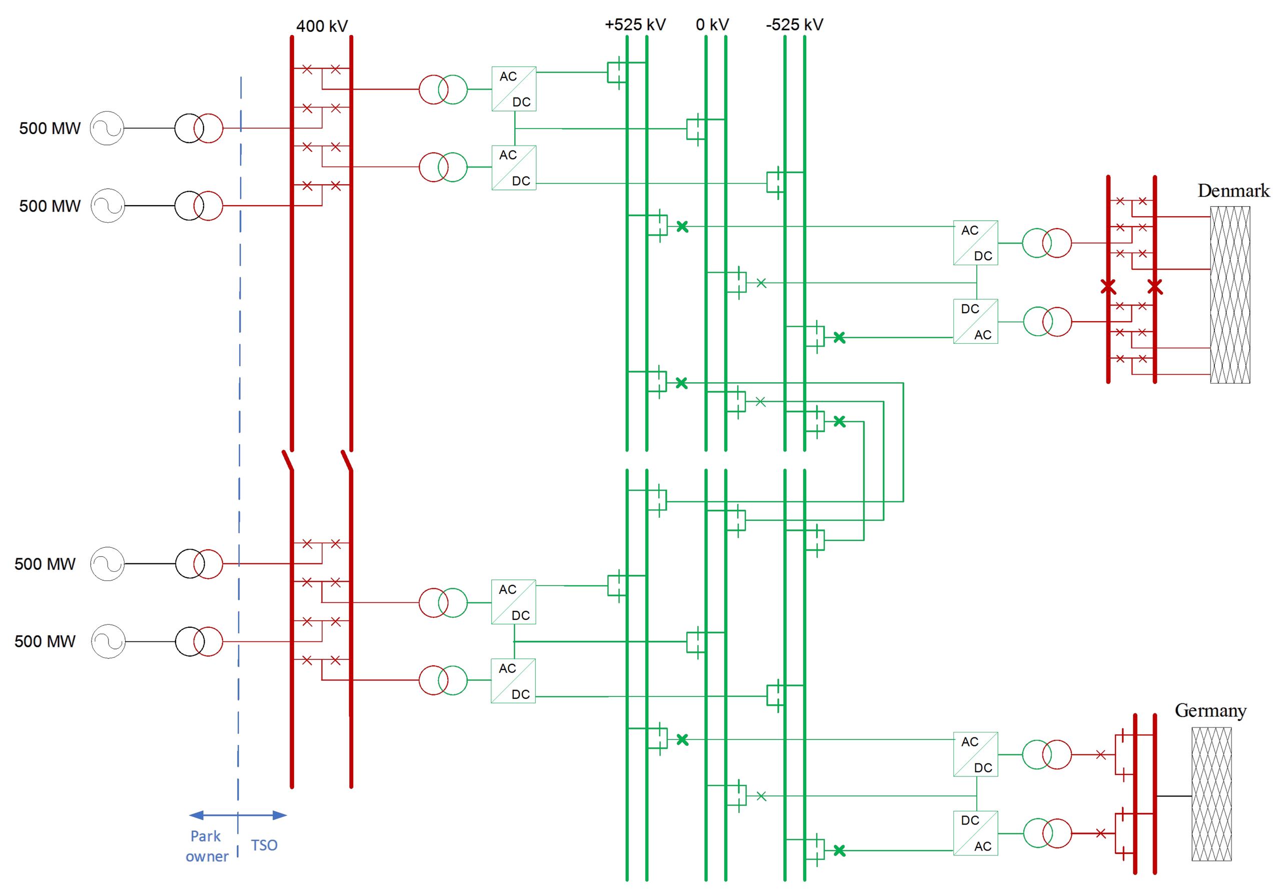
| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|---|---|---|---|---|---|
| Grid EENT | 10,84 | 10,84 | 10,83 | 10,83 | 11,10 |
| Both EENT | 0,27 | 0,27 | 0,28 | 0,28 | 0,00 |
| Protection EENT | 0,07 | 0,07 | 0,11 | 0,11 | 0,00 |

d2) Scenario 2b 750 MW loss of infeed, 320 kV Losses (MWh/h)

| | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
|---|---|---|---|---|---|
| Inductor_Loss | 1,15 | 1,34 | 0,72 | 0,78 | 0,00 |
| Cable Loss | 11,99 | 11,99 | 11,99 | 11,99 | 12,03 |
| Transformer Loss | 9,18 | 9,18 | 9,18 | 9,18 | 9,96 |
| Converter Loss | 23,44 | 23,44 | 31,65 | 23,44 | 25,42 |

## Developments after PROMOTioN

Energinet and 50Hertz have signed cooperation agreement to make it happen.




## Conclusion

A technoeconomic feasibility assessment for the transmission system of Bornholm energy islands was performed. The implementation on the actual project is responsibility of the TSOs involved, but the methodology can be used to inspire the decision making.

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