North Sea Transnational Grid (NSTG)
Project introduction and Work package 2

Final NSTG project meeting
Delft, 13-6-2014

Jan Pierik, ECN

NSTG project objectives

- determine the best solution (modular, flexible, most cost effective) for a high capacity NSTG, connecting future wind farms in the northern part of the North Sea to the Netherlands, UK, Norway, Denmark and Germany.
- develop, test and optimize a multi-terminal DC grid controller
- investigate the effects of the NSTG on the national grids:
  - develop the operating strategy of the NSTG to regulate power exchange correctly and avoid congestion
  - investigate the effect of the NSTG on national grid stability.
- investigate the costs, benefits, policies and regulations related to realization of the NSTG and compare to alternative scenarios.

NSTG work packages

1. Inventory of available technology, modularity and flexibility
2. Technical and economic evaluation of different solutions
3. Transnational Grid multi-terminal operation and control
4. Multi-terminal converter testing on RTDS
5. Optimization
6. Grid integration: planning, congestion and
7. Grid integration: stability
8. Costs, benefits, regulations and market aspects North Sea
9. International collaboration (IEA Annex 25)
10. Dissemination of results
11. Project coordination and administration

WP2: Techno-economic evaluation

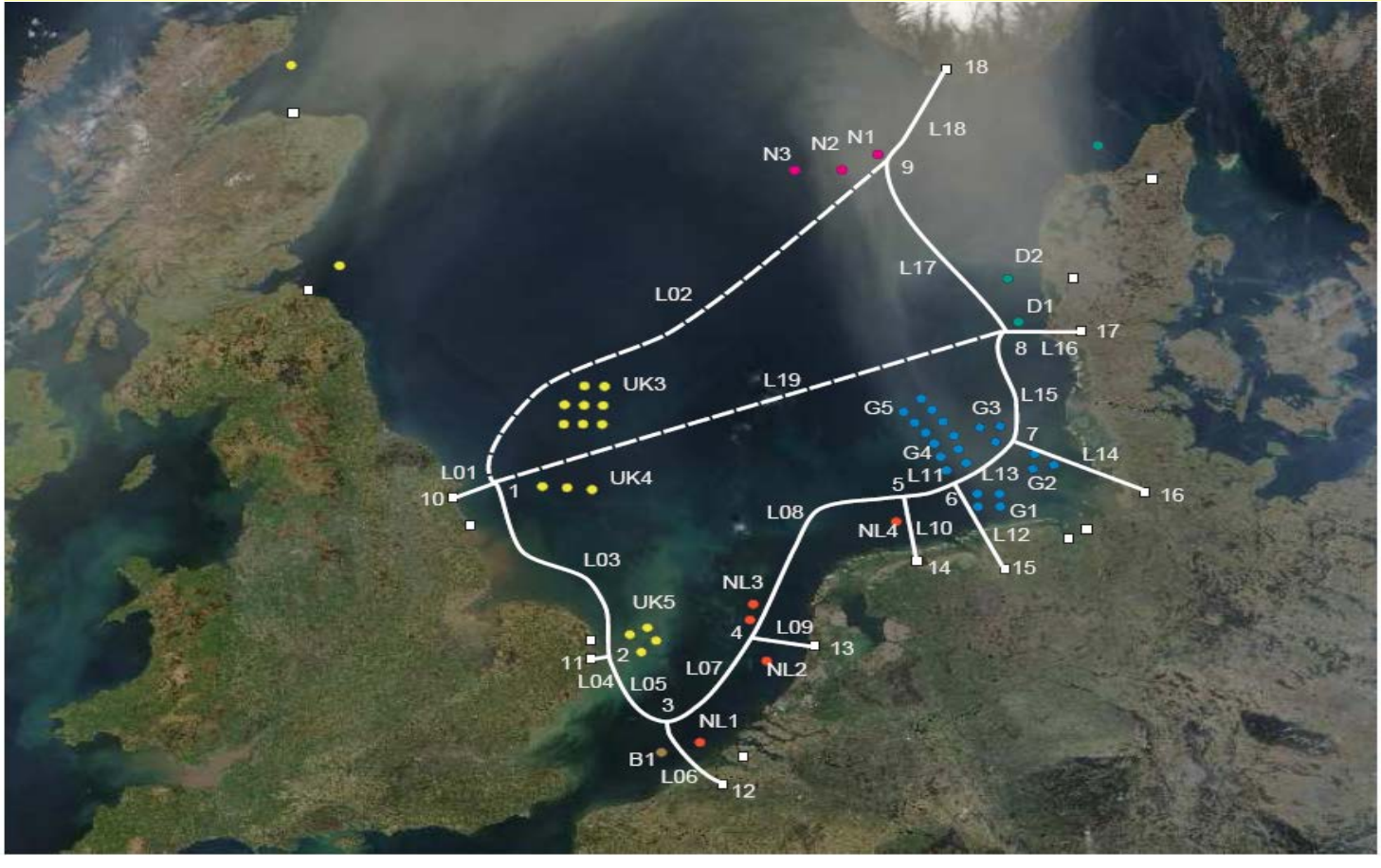
Objectives:

- Compare energy production and costs of options for NSTG with 57600 MW wind power
- Calculate 10 development stages
- Compare integrated and non-integrated option
- Compare options with AC and DC connected WFs

Assumptions

- WF locations and transnational connections →next slide
- Number of WFs and number of transnational connections in different stages → next slide
- WF rated power: 1100MW
- WF DC connections:
  - +/-320kVDC, 1216MW VSC, 2x1x1200 mm2 DC cable
- Trade connections:
  - +/-320kVDC, 2x1x1200 mm2 DC cable
- WF AC connections:
  - 150kV, 6(7)x1x3x800 mm2 AC cable

NSTG WF locations and trade connections



Number of WFs and connections

New 1100 MW wind farms and corresponding connections per development phase and location											
Location		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
UK3 (C)	Dog						2 (2)	1 (3)	2 (5)	1 (6)	2 (8)
UK4 (C)	Hor				2 (2)	1 (3)	(3)	(3)	(3)	(3)	(3)
UK5 (F)	Nor	1 (1)	2 (3)	1 (4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)
B1 (G)	Tho						1 (1)	(1)	(1)	(1)	(1)
NL1 (G)	Bor									1(1)	(1)
NL2 (I)	IJmA	1 (1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
NL3 (I)	IJmB					1 (1)	(1)	1 (2)	(2)	(2)	(2)
NL4 (J)	Eem			1 (1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
G1 (K)	Bor	2 (2)	2 (4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)
G2 (M)	Aus			2 (2)	1 (3)	(3)	(3)	(3)	(3)	(3)	(3)
G3 (M)	Amr				1	2 (3)	(3)	(3)	(3)	(3)	(3)
G4 (K)	HoS						3 (3)	2 (5)	1 (6)	(6)	(6)
G5 (K)	HoN								2 (2)	2 (4)	2 (6)
D1 (N)	HR	1 (1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
D2 (N)	Rin						1 (1)	(1)	(1)	(1)	(1)
N1 (Q)	Lys	1 (1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
N2 (Q)	Ægi				1 (1)	(1)	(1)	(1)	(1)	(1)	(1)
N3 (Q)	Idu							1 (1)	(1)	(1)	(1)
Total number of 1100 MW wind farms and corresponding connections per country											
UK		1	3	4	6	7	9	10	12	13	15
B							1	1	1	1	1
NL		1	1	2	2	3	3	4	4	5	5
G		2	4	6	8	10	13	15	18	20	22
D		1	1	1	1	1	2	2	2	2	2
N		1	1	1	2	2	2	3	3	3	3
Total		6	10	14	19	23	30	35	40	44	48

NSTG connections–
Wind – Trade – Trade to shore

— A — Wind farm to shore

Grid section		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
L01	UK				2	3	5	6	8	9	11
L04	UK	1	3	4	4	4	4	4	4	4	4
L06	B						1	1	1	2	2
L09	NL	1	1	1	1	2	2	3	3	3	3
L10	NL			1	1	1	1	1	1	1	1
L12	G	2	4	4	4	4	7	9	11	14	16
L14	G			2	4	6	6	6	6	6	6
L16	DK	1	1	1	1	1	2	2	2	2	2
L18	N	1	1	1	2	2	2	3	3	3	3
Total		6	10	14	19	23	30	35	40	44	48

— B — Country to country

Grid section		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
L03	UK				1	1	1	1	1	1	1
L05	UK-B	1	1	1	2	2	2	2	3	3	3
L07	B-NL	1	1	1	1	1	2	2	2	2	2
L08	NL-NL	1	1	1	1	1	2	2	2	2	2
L11	NL-G	1	1	2	2	2	2	2	2	2	2
L13	G-G	1	1	2	2	2	2	2	2	2	2
L15	G-DK	1	1	1	1	2	2	2	2	2	2
L17	DK-N	1	1	1	1	2	2	2	2	2	2
L02	N-UK						1	1	2	2	2
L19	D-UK					1	1	1	1	1	1
Total		7	7	9	11	14	17	17	19	19	19

— C — Trade only to shore

Grid section		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
L01	UK				1	2	3	3	3	3	3
L04	UK	1	1	1	2	2	2	2	2	2	2
L06	B		1	1	1	1	1	1	1	1	1
L09	NL	1	1	1	1	1	1	1	2	2	2
L10	NL			1	1	1	1	1	1	1	1
L12	G	1	1	1	1	1	1	2	2	2	2
L14	G			1	1	1	1	1	1	1	2
L16	DK		1	1	1	2	2	2	2	2	2
L18	N	1	1	1	1	1	2	2	2	2	2
Total		4	6	8	10	12	14	15	16	16	17

Assumptions (2)

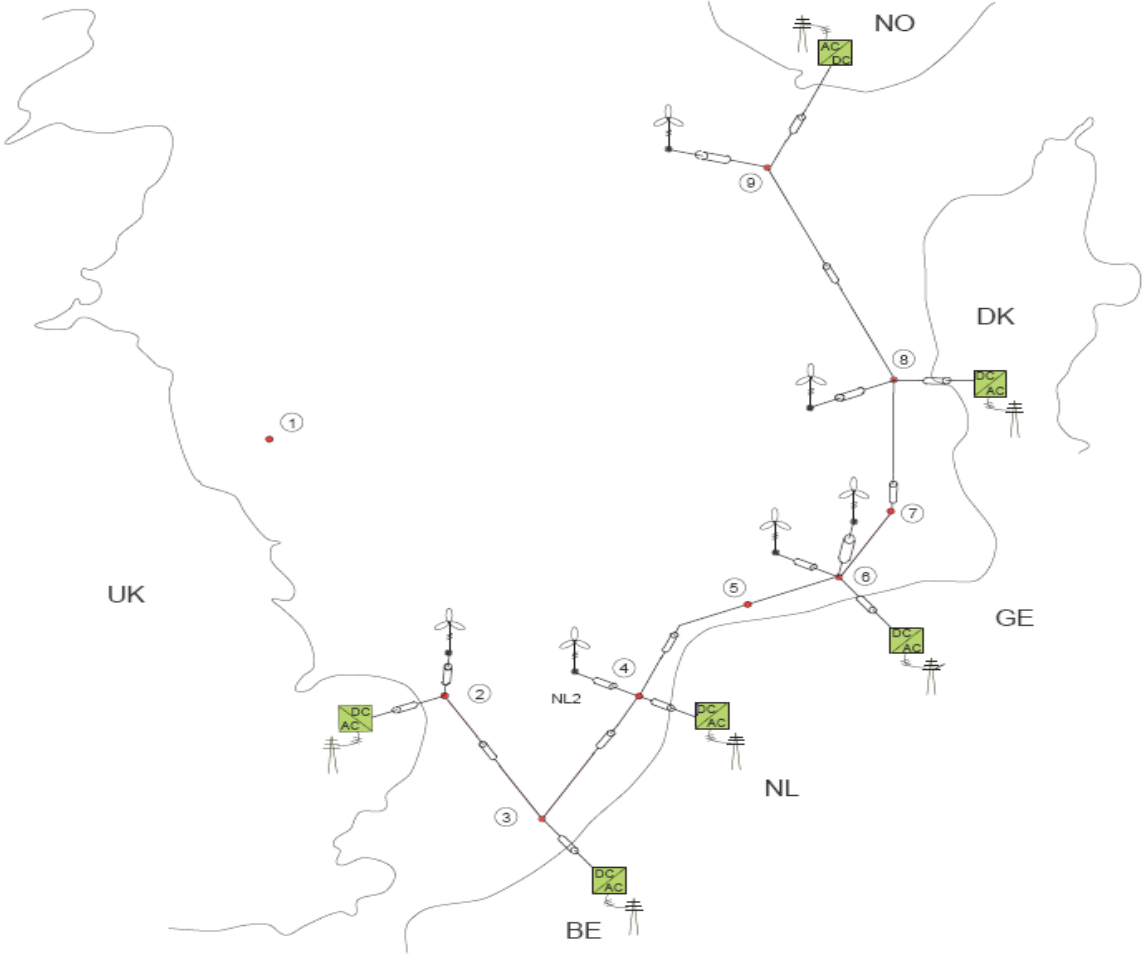
- Component costs based on manufacturer data (2009) but corrected for recent price developments (ENTSOe, Irene-40, interconnection projects)
- WF to shore:
  - LTC based on wind power only
- Transnational sections:
  - lower total rating than most WF to shore connections
  - LTC based on maximum power
- Non-integrated scenario:
  - required additional DC connections to shore for trade only

Scenarios

- Scenario 1:
  - wind and trade connections integrated = all DC
- Scenario 2:
  - wind and trade connections separate = AC and DC

- Wind and trade connections are evaluated separately and results are added

Scenario 1: Wind Trade integrated – Phase 1

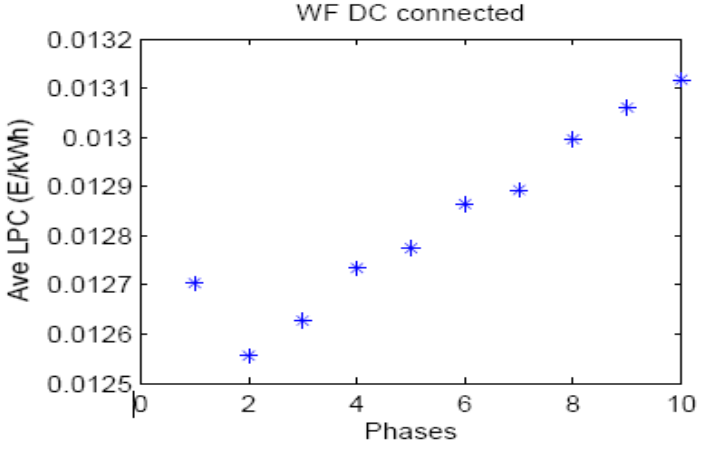


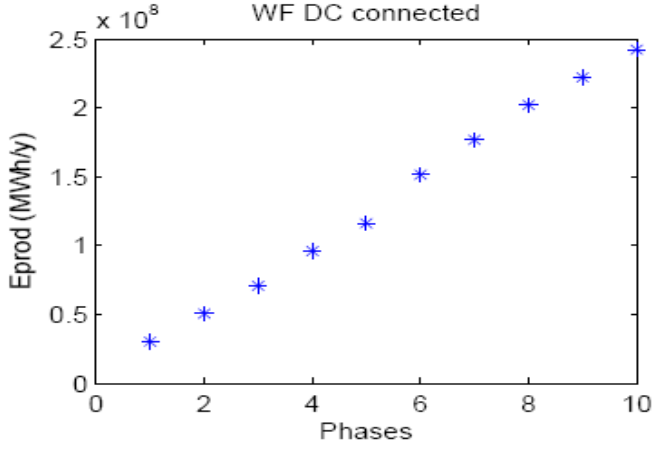
Scenario 1 – part 1: WF DC connected

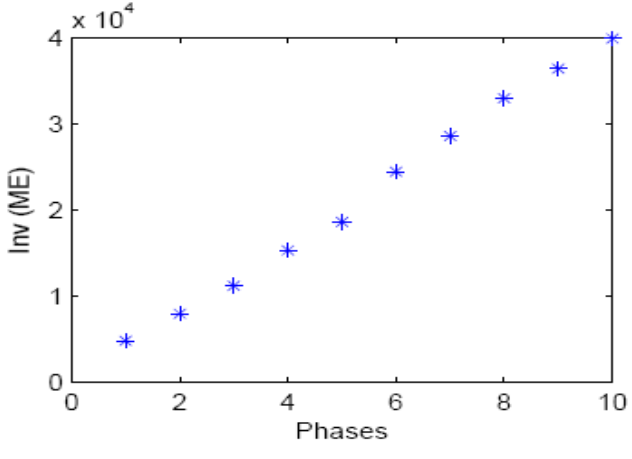
Wind Farms DC connected: all NSTG phases total sums and averages

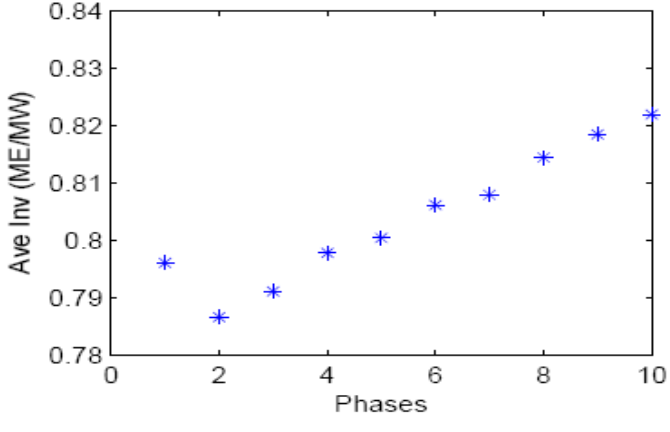
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	4816.2	7968.1	11215.7	15339.5	18638.5
Pmax (MW)	6049.6	10128.9	14176.7	19226.2	23284.8
Etotal (GWh/y)	30170.8	50513.5	70704.5	95892.8	116141.5
Elosses (GWh/y)	1973.6	3276.4	4601.4	6272.8	7610.4
Elosses (%)	6.5	6.5	6.5	6.5	6.6
Efail (GWh/y)	699.8	951.7	1332.3	1843.1	2153.8
Efail (%)	2.3	1.9	1.9	1.9	1.9
Inv per MW (MEuro/MW)	0.7961	0.7867	0.7911	0.7978	0.8005
LTC ave (Euro/kWh)	0.01270	0.01256	0.01263	0.01273	0.01277
	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	24470.6	28623.8	32975.6	36451.1	39941.3
Pmax (MW)	30353.1	35426.6	40487.6	44534.6	48590.4
Etotal (GWh/y)	151409.4	176713.7	201960.3	222141.2	242363.4
Elosses (GWh/y)	9964.5	11643.7	13370.5	14750.5	16138.9
Elosses (%)	6.6	6.6	6.6	6.6	6.7
Efail (GWh/y)	2850.6	3238.4	3636.4	3972.6	4264.0
Efail (%)	1.9	1.8	1.8	1.8	1.8
Inv per MW (MEuro/MW)	0.8062	0.8080	0.8145	0.8185	0.8220
LTC ave (Euro/kWh)	0.01286	0.01289	0.01300	0.01306	0.01312

WF DC connected – all phases







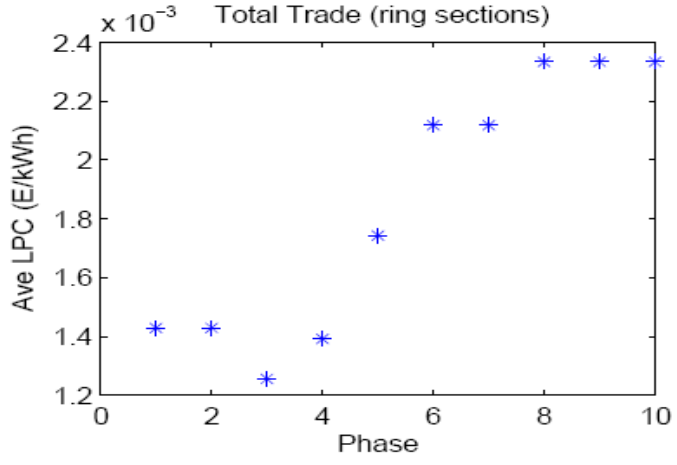


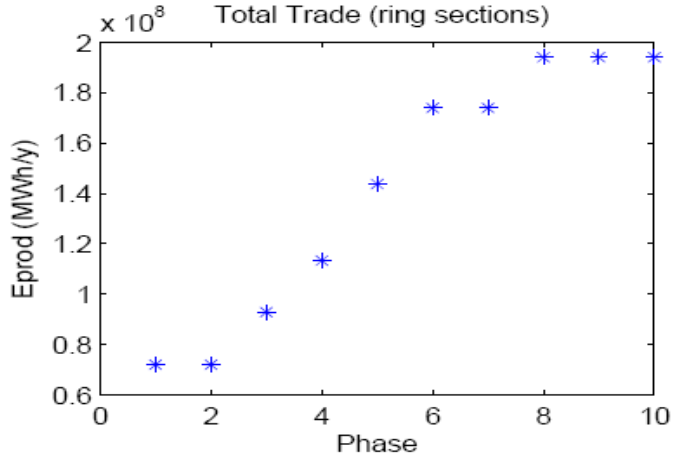
Scenario 1 and 2 – part 2: Transnational DC

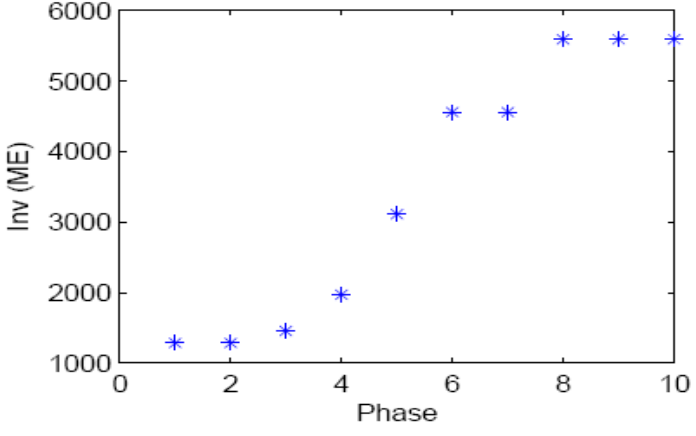
NSTG DC Ring - Country to country sections: all development phases

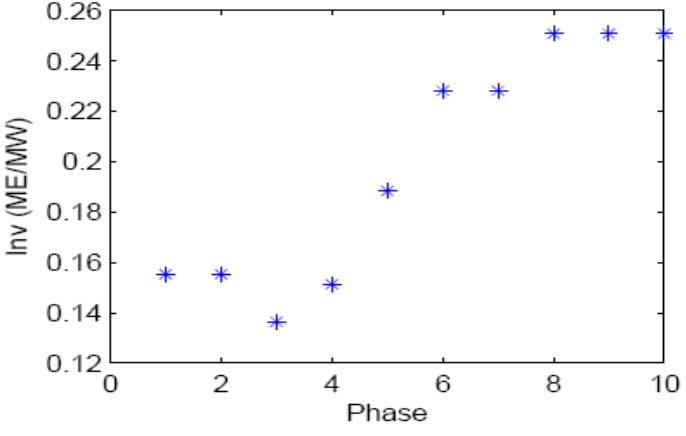
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	1286.8	1286.8	1455.9	1970.7	3110.4
Pmax (MW)	8283.1	8283.1	10667.7	13020.9	16517.6
Etotal (GWh/y)	72107.1	72107.1	92866.1	113351.9	143791.4
Elosses (GWh/y)	926.6	926.6	1048.6	1419.1	2238.1
Elosses (%)	1.3	1.3	1.1	1.3	1.6
Efail (GWh/y)	89.8	89.8	101.7	137.5	215.3
Efail (%)	0.1	0.1	0.1	0.1	0.1
Inv per MW (MEuro/MW)	0.1554	0.1554	0.1365	0.1513	0.1883
LTC ave (Euro/kWh)	0.00143	0.00143	0.00126	0.00139	0.00174
	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	4559.0	4559.0	5588.5	5588.5	5588.5
Pmax (MW)	19986.3	19986.3	22293.0	22293.0	22293.0
Etotal (GWh/y)	173987.8	173987.8	194069.0	194069.0	194069.0
Elosses (GWh/y)	3278.3	3278.3	4017.0	4017.0	4017.0
Elosses (%)	1.9	1.9	2.1	2.1	2.1
Efail (GWh/y)	313.4	313.4	382.6	382.6	382.6
Efail (%)	0.2	0.2	0.2	0.2	0.2
Inv per MW (MEuro/MW)	0.2281	0.2281	0.2507	0.2507	0.2507
LTC ave (Euro/kWh)	0.00212	0.00212	0.00233	0.00233	0.00233

Transnational sections for trade – all phases

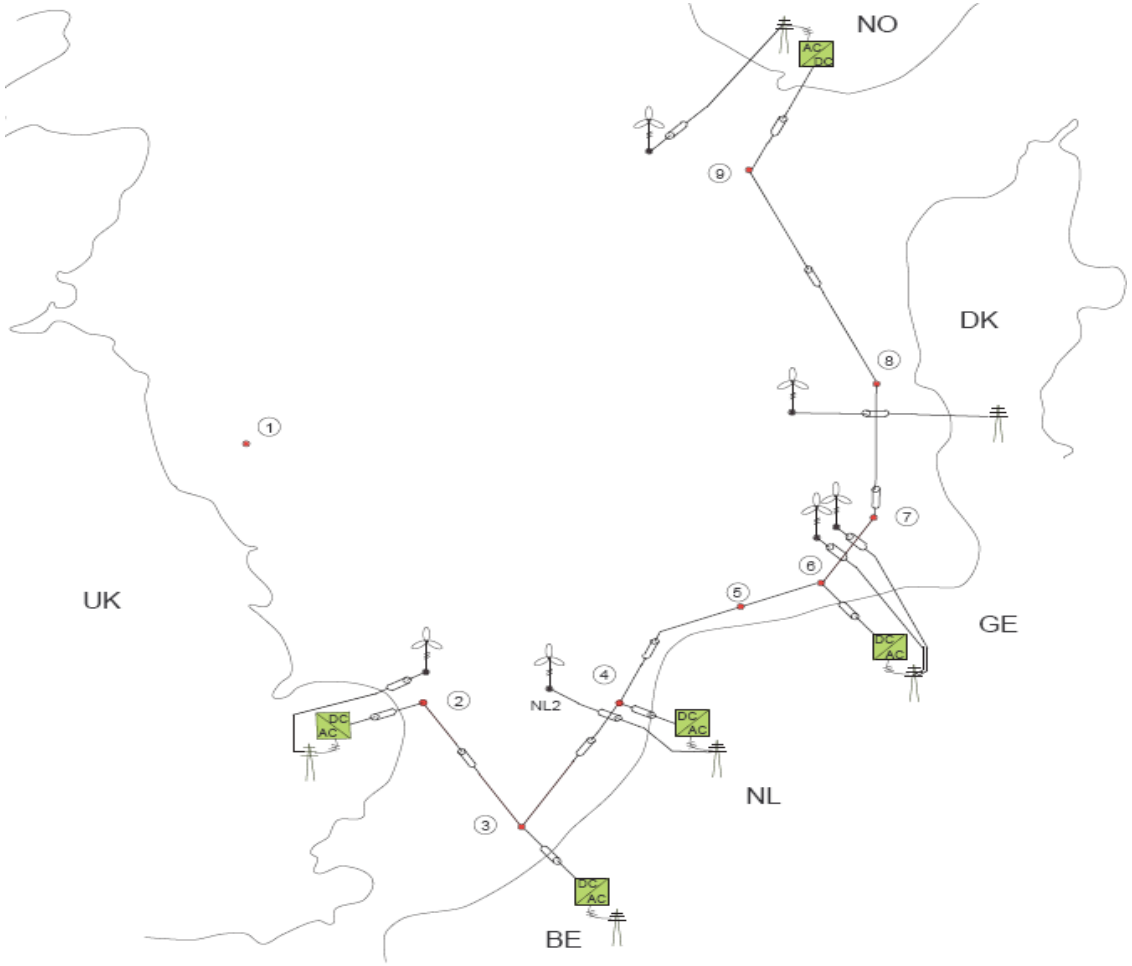








Scenario 2: Wind &Trade not connected – Phase 1

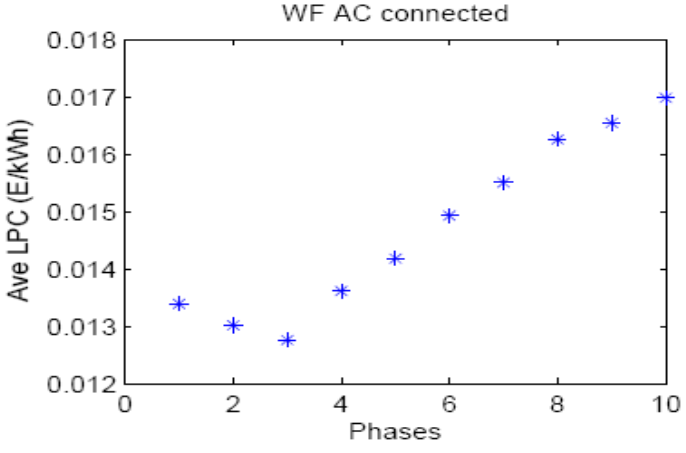


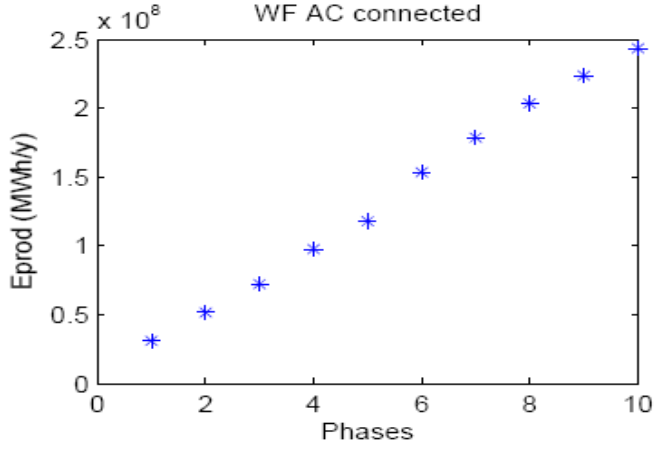
Scenario 2 – part 1: Wind AC

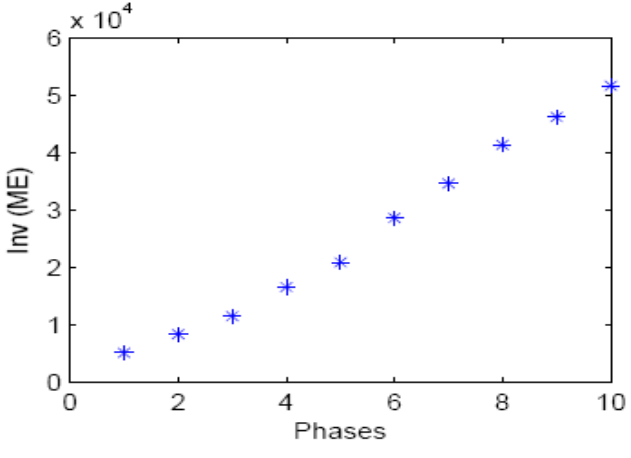
Wind Farms AC connected: all phases

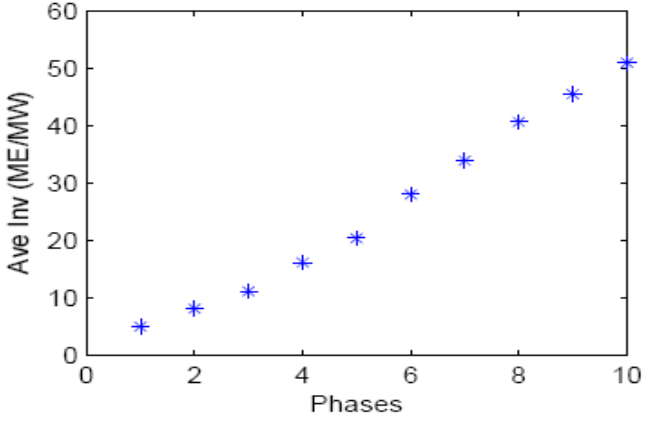
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	5171.2	8394.9	11534.8	16641.1	20927.4
Pmax (MW)	6176.2	10301.4	14434.6	19528.4	23592.2
Etotal (GWh/y)	30848.3	51462.4	72113.0	97553.6	117846.9
Elosses (GWh/y)	1956.7	3206.9	4419.9	6330.5	7922.3
Elosses (%)	6.3	6.2	6.1	6.5	6.7
Efail (GWh/y)	66.3	110.8	155.2	210.2	254.1
Efail (%)	0.2	0.2	0.2	0.2	0.2
Inv per MW (MEuro/MW)	0.8373	0.8149	0.7991	0.8521	0.8870
LTC ave (Euro/kWh)	0.01339	0.01301	0.01275	0.01361	0.01418
	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	28661.6	34653.5	41391.0	46255.3	51697.6
Pmax (MW)	30711.7	35760.6	40759.3	44789.2	48783.2
Etotal (GWh/y)	153380.5	178583.4	203504.1	223589.8	243498.3
Elosses (GWh/y)	10692.6	12857.4	15329.5	17152.4	19160.8
Elosses (%)	7.0	7.2	7.5	7.7	7.9
Efail (GWh/y)	330.2	384.6	438.8	482.5	525.9
Efail (%)	0.2	0.2	0.2	0.2	0.2
Inv per MW (MEuro/MW)	0.9332	0.9690	1.0155	1.0327	1.0597
LTC ave (Euro/kWh)	0.01493	0.01550	0.01626	0.01654	0.01698

Wind AC connected – all phases







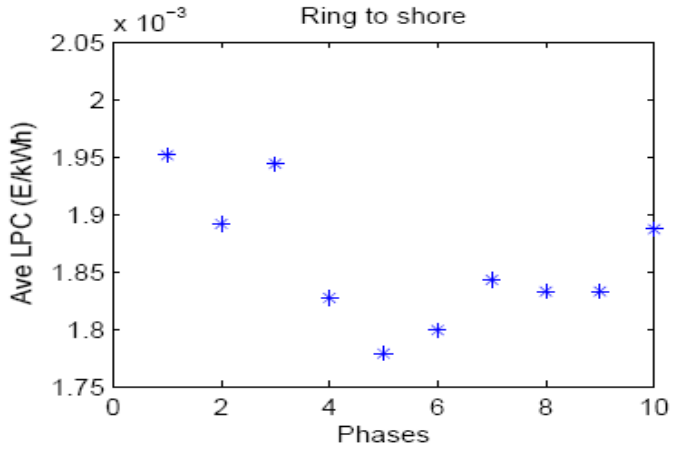


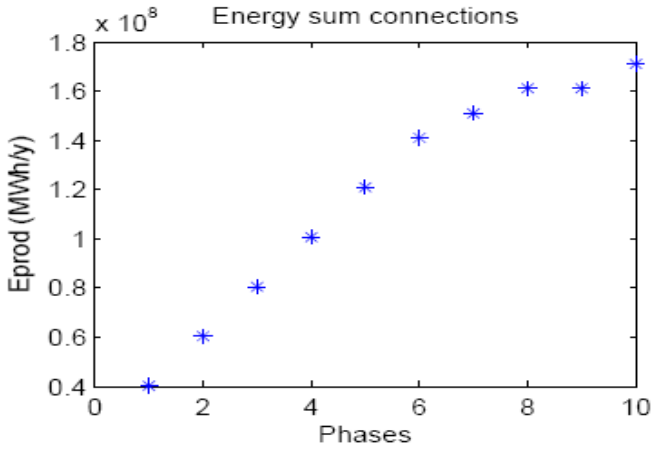
Scenario 2 – part 3: Trade to shore (DC)

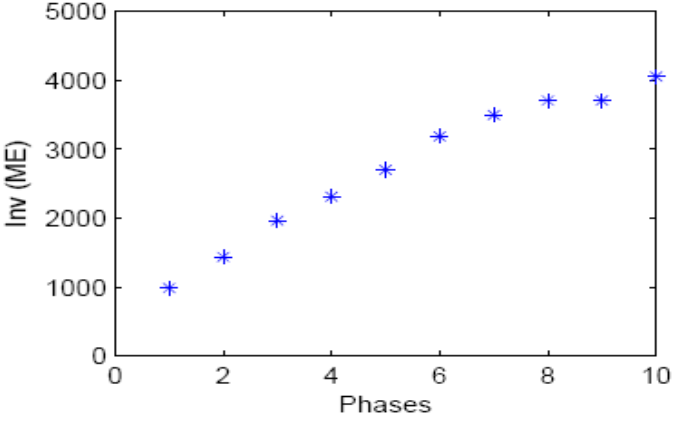
Trade connections to shore all phases: results per phase

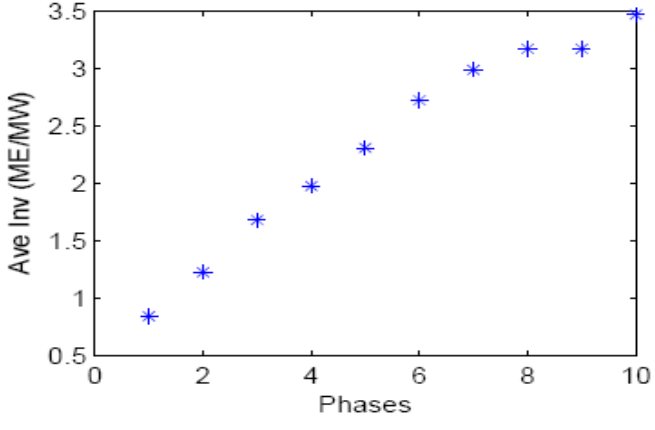
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	985.3	1433.9	1963.3	2308.9	2698.6
Pmax (MW)	4621.3	6935.9	9243.3	11567.0	13886.9
Etotal (GWh/y)	40230.2	60379.4	80466.0	100695.2	120890.1
Elosses (GWh/y)	1107.3	1629.5	2209.3	2658.2	3138.5
Elosses (%)	2.8	2.7	2.7	2.6	2.6
Efail (GWh/y)	440.5	658.0	880.5	1091.6	1305.5
Efail (%)	1.1	1.1	1.1	1.1	1.1
Inv per MW (MEuro/MW)	0.2132	0.2067	0.2124	0.1996	0.1943
LTC ave (Euro/kWh)	0.00195	0.00189	0.00194	0.00183	0.00178
	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	3183.9	3492.7	3706.0	3706.0	4051.5
Pmax (MW)	16198.2	17347.9	18506.2	18506.2	19652.7
Etotal (GWh/y)	141010.8	151019.9	161103.1	161103.1	171083.7
Elosses (GWh/y)	3686.9	4008.2	4261.5	4261.5	4609.0
Elosses (%)	2.6	2.7	2.6	2.6	2.7
Efail (GWh/y)	1525.2	1639.2	1747.3	1747.3	1863.6
Efail (%)	1.1	1.1	1.1	1.1	1.1
Inv per MW (MEuro/MW)	0.1966	0.2013	0.2003	0.2003	0.2062
LTC ave (Euro/kWh)	0.00180	0.00184	0.00183	0.00183	0.00189

Trade to shore – all phases (scenario 2 only)









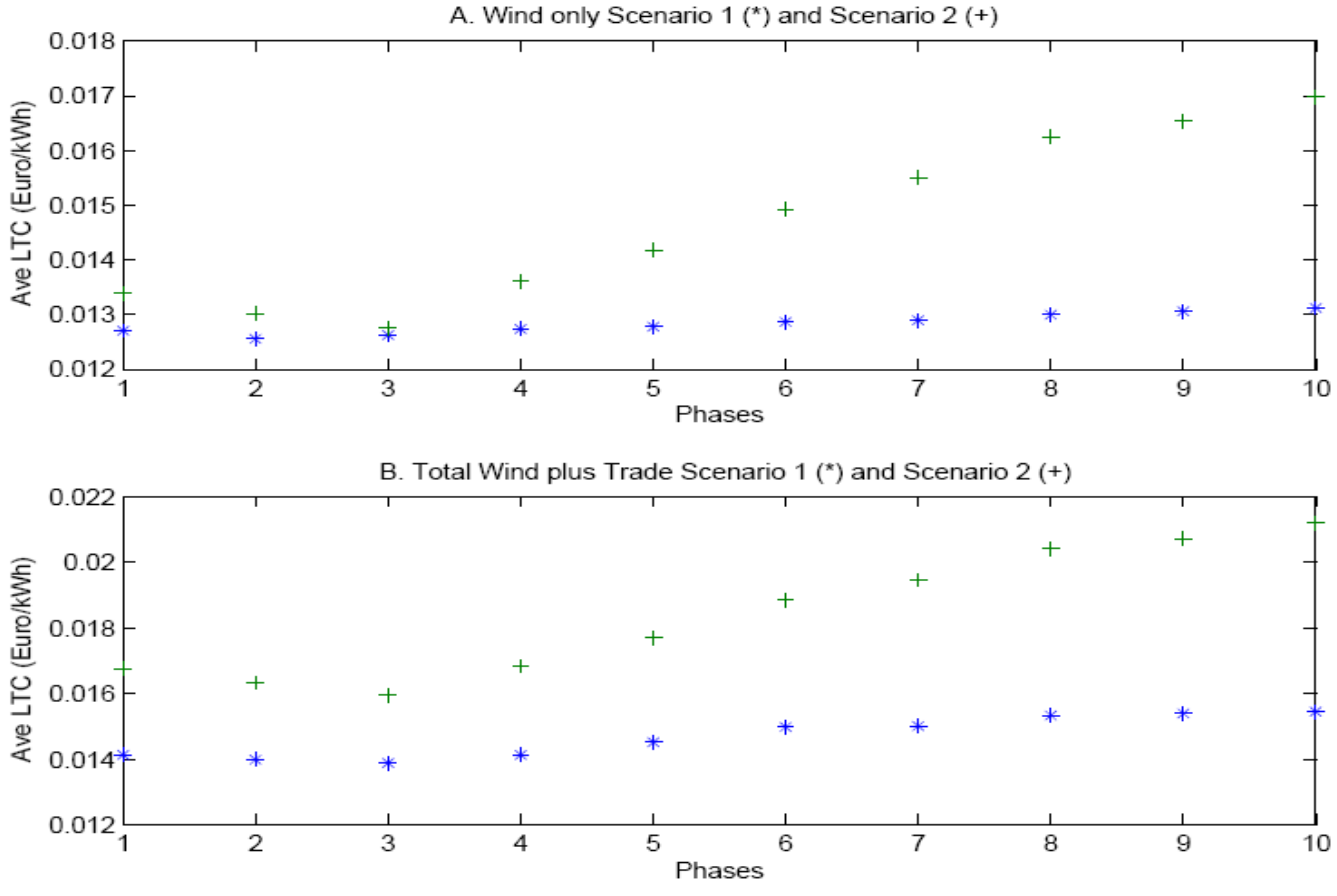
Wind in scenario 1 (DC) and 2 (AC)

Scenario 1 and 2: Wind connections only

Scenario 1: Wind DC	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
number of WF	6	10	14	19	23
Inv (MEuro)	4816.2	7968.1	11215.7	15339.5	18638.5
LTC ave (Euro/kWh)	0.01270	0.01256	0.01263	0.01273	0.01277
Scenario 2: Wind AC	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
number of WF	6	10	14	19	23
Inv (MEuro)	5171.2	8394.9	11534.8	16641.1	20927.4
LTC ave (Euro/kWh)	0.01339	0.01301	0.01275	0.01361	0.01418

Scenario 1: Wind DC	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
number of WF	30	35	40	44	48
Inv (MEuro)	24470.6	28623.8	32975.6	36451.1	39941.3
LTC ave (Euro/kWh)	0.01286	0.01289	0.01300	0.01306	0.01312
Scenario 2: Wind AC	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
number of WF	30	35	40	44	48
Inv (MEuro)	28661.6	34653.5	41391.0	46255.3	51697.6
LTC ave (Euro/kWh)	0.01493	0.01550	0.01626	0.01654	0.01698

Wind in scenario 1 (DC) and 2 (AC)



Trade in scenario 1 (integrated) and 2 (separate)

Trade connections only in Scenario 1 and 2 per phase

Scenario 1 and 2: Ring (Trade)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
number of trade connections	7	7	9	11	14
Inv (MEuro)	1286.8	1286.8	1455.9	1970.7	3110.4
LTC ave (Euro/kWh)	0.00143	0.00143	0.00126	0.00139	0.00174
Scenario 2: Trade to Shore	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
number of trade connections to shore	4	6	8	10	12
Inv (MEuro)	985.3	1433.9	1963.3	2308.9	2698.6
LTC ave (Euro/kWh)	0.00195	0.00189	0.00194	0.00183	0.00178

Scenario 1 and 2: Ring (Trade)	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
number of trade connections	17	17	19	19	19
Inv (MEuro)	4559.0	4559.0	5588.5	5588.5	5588.5
LTC ave (Euro/kWh)	0.00212	0.00212	0.00233	0.00233	0.00233
Scenario 2: Trade to Shore	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
number of trade connections to shore	14	15	16	16	17
Inv (MEuro)	3183.9	3492.7	3706.0	3706.0	4051.5
LTC ave (Euro/kWh)	0.00180	0.00184	0.00183	0.00183	0.00189

Scenario 1 and 2 : Wind and trade combined

Scenario 1 and 2: Wind and Trade Total (Electrical system only, wind turbines not included)

Scenario 1: Wind DC + Trade	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	6103.0	9255.0	12671.6	17310.1	21748.9
LTC ave (Euro/kWh)	0.01413	0.01398	0.01388	0.01413	0.01452
Scenario 2: Wind AC + Trade	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	7443.3	11115.6	14954.0	20920.6	26736.4
LTC ave (Euro/kWh)	0.01676	0.01633	0.01595	0.01683	0.01770

Scenario 1: Wind DC + Trade	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	29029.6	33182.8	38564.0	42039.5	45529.7
LTC ave (Euro/kWh)	0.01498	0.01501	0.01533	0.01539	0.01545
Scenario 2: Wind AC + Trade	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	36404.5	42705.2	50685.4	55549.7	61337.6
LTC ave (Euro/kWh)	0.01884	0.01946	0.02042	0.02071	0.02120

Conclusions

- Investment costs play a dominant role
- Wind to shore connections:
  - scenario 1 (DC) lowest average LTC in all phases
- Trade connections:
  - scenario 1 (interconnected DC) lowest average LTC
- Wind and trade connections together:
  - scenario 1 (interconnected DC) lowest average LTC in all phases