Workstream 3
All-Island Grid Study
Report

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Preface

The All Island Grid Study is the first comprehensive assessment of the ability of the electricity transmission network (“the grid”) on the island of Ireland to absorb large amounts of electricity produced from renewable energy sources.

On July 25th 2005 the then Department of Communications, Marine and Natural Resources in the Republic of Ireland and the Department of Enterprise, Trade and Investment in Northern Ireland jointly issued a preliminary consultation paper on an all-island ‘2020 Vision’ for renewable energy. The paper sought views on the development of a joint strategy for the provision of renewable energy sourced electricity within the All-island Energy Market leading up to 2020 and beyond, so that consumers, North and South, continue to benefit from access to sustainable energy supplies provided at a competitive cost.

It is within the context of the All-island Energy Market Development Framework agreed by Ministers and the undertaking to develop a Single Electricity Market that consideration was given to how the electricity infrastructure on the island might best develop to allow the maximum penetration of renewable energy.

The consultation paper identified that further information was required on the resource potential for different renewable electricity technologies on the island of Ireland in 2020, the extent to which partially dispatchable and non-dispatchable generation could be accommodated, network development options and the economic implications of the options outlined within the paper.

A working group was established to specify and oversee the completion of studies that would provide more detailed information on the above issues The working group recommended an “All Island Grid Study” comprised of 4 work-streams detailed below.

- Work-stream 1 is a resource assessment study.

- Work-stream 2 investigates the extent non-dispatchable or partially dispatchable generation can be accommodated on the grid system with regard to variability and predictability.

  This work-study comprises two stages:

  (a) an initial high level modelling study to determine the portfolios to be studied.

  (b) a dynamic modelling study of the impact of renewable generation on grid operation, costs and emissions.

- Work-stream 3 looks at the engineering implications for the grid, in terms of the extent and cost of likely network reinforcements to accommodate the specified renewable inputs.

- Work-stream 4 uses the outputs of earlier work streams to investigate the economic impact and benefits of various renewable generation levels. It also investigates the stakeholder impacts and perceptions of various options for cost recovery. It is the “techno-economic wrapper” report which presents high-level results for policy makers.

Executive Summary

The main objective of Work-stream 3 All Island Grid Study was to investigate the extent of network development for a range of renewable generation penetration levels based on the generation portfolios developed by Work-stream 2a.

The overloaded lines identified in this work-stream are mainly located in the areas where significant wind installed capacities are anticipated such as Co. Mayo, Co. Sligo and Co. Donegal, South-West, Northern Ireland, Co. Waterford and Co. Wexford. The higher the wind penetration in these areas the bigger the extent of the problem in terms of the number of overloads. In addition to these areas it was found that in Portfolio 5 and Portfolio 6 a significant number of the 110 kV lines connected to the Flagford substation becomes overloaded.

The work-stream studies indicated that for Portfolios 2,3 and 4 (wind installed capacity is 4,000MW), the transmission network would suffer overloads on 30-40 circuits. For Portfolio 5 (wind installed capacity is 6,000MW) the system would suffer overloads on 50-60 circuits. For Portfolio 6 (wind installed capacity is 8000MW), the renewable penetration of 6,900MW is designated as a ‘knee point’. For those wind penetrations larger than the ‘knee point’ the number of overloads was almost doubled with respect to Portfolio 5. It was found that for renewable penetrations larger than the identified ‘knee point’ the network reinforcement problem becomes a network re-design problem. Therefore, for Portfolio 6 the network reinforcement studies were carried out only for up to 6,900 MW of renewable penetration.

A summary of the proposed network reinforcements required to ensure N-1 power system security is given in the following table:

	Portfolio 6A	Portfolio 6B	Portfolio 5	Portfolios 4,3,2	Portfolio 1
Total length (km) of new 220 or 275 kV lines (km of double circuits)	498 (254)	370 (262)	370 (227)	282 (130)	n.a.
Total length (km) of new 110 kV lines	255	294	228	182	37.4
Total length (km) of uprated 110 kV lines	216	253	190	191	37.4

In addition to the new lines and the uprating of existing lines summarised in the table above, up to 2400 MVAr of additional reactive power compensation will be required to ensure that the Irish 2020 power system can meet the voltage requirements stipulated by the existing planning standards. Reactive support will be mainly required in the following regions: North-East, Dublin region, South-West and Northern Ireland.

Voltage security analysis showed that one of the main challenges for the 2020 Irish power system will be voltage and reactive power control considering that a significant number of conventional units capable of providing reactive power and located electrically relatively close to the load centres will be replaced by wind generation electrically which is far from the load centres and which has limited capability to provide reactive power.

The calculation of network reinforcement costs shows that the costs increase with the level of renewable generation. Thus, the smallest reinforcement costs are for Portfolio 1 (€92M) taking into account that the considered renewable power output for this portfolio is the smallest (about 2,200 MW). On the other hand, the considered renewable power output for Portfolio 6A is about 6,900 MW and the estimated reinforcement costs is the highest at €1,239M.

The network reinforcement costs for Portfolio 6B are €1,090M, for Portfolio 5 are €1,006M, while for Portfolio 2,3 and 4 these costs vary between €668M and €690M.

A significant portion of the network reinforcement costs in Portfolio 2 to Portfolio 6 is associated with the construction of new 220/275 kV network. The cost of additional reactive power support is between 15-18%, and the network reinforcement costs for the 110 kV network are between 13% and 19%.

It is clear that the extent of the network reinforcements in Co.Mayo, Co. Sligo and Co.Donegal is significantly larger than for all other regions. For example in Portfolio 5 (6GW installed wind capacity) the total costs calculated for these counties are €318M, while for Northern Ireland and South-West these costs are €292M and €135M, respectively.

The biggest step in terms of the network reinforcements is the move from a wind power installed capacity of 2GW in Portfolio 1 to 4GW in Portfolios 2, 3, 4 with an incremental cost of €576M.

1 Introduction

The electricity system in Ireland has a peak demand of around 7GW and consists of the Northern Ireland and Republic of Ireland systems that have AC interconnections and are operated synchronously by two transmission system operators (Eirgrid and SONI). There is a HVDC interconnection with a capacity of 500 MW between the Northern Ireland system and the electricity system in Scotland.

The Republic of Ireland and Northern Ireland governments promote the development of electricity generation from renewable sources. Ireland has a good wind and other renewable potential. In order to investigate the technical and economic challenges of the integration of intermittent renewable generation sources on a large scale a series of comprehensive technical and economic studies have been commissioned by the Irish governments and grid operators through the following work-streams:

- Work-stream 1 – is a resource assessment whose objective is to identify the size, location and cost of renewable energy developments.
- Work-stream 2 - which is focused on unit commitment studies to investigate the operational limitations and costs caused by inflexibilities of conventional generating units.
- Work-stream 3 – which is the focus of this report whose objective is to investigate and assess the extent and potential cost of network developments required for Ireland’s 2020 electricity system.
- Workstream 4 that deals with the economic impact of various levels of renewables and draws overall conclusions from the whole study.

Work-stream 3 comprises two tasks: Task 1- a ‘first-pass security assessment’ whose objective is to identify the line overloads and bottlenecks using DC load flow techniques and Task 2- a comprehensive security assessment based on AC load flow based techniques.

Both tasks deal with six different generation portfolios. It should be pointed out that the Working Group requested to study an additional Portfolio 6 after the completion of Task 1. This is why the Task 1 studies include only Portfolio 6A, why the Task 2 studies include both Portfolio 6A and Portfolio 6B. The only difference between these two portfolios is in wind resource distribution (see *Appendix A*). Thus, Portfolio 6A studied in Task 1 has 1 GW of offshore wind generation added on the Working Group request, while Portfolio 6B is based purely on indicative levelised cost criteria that led to only 70 MW of offshore wind generation in this portfolio.

Task 1 identifies the network overloads for a significant number of randomly chosen operational scenarios. The results are characterised in terms of the most frequently overloaded lines and those that cause overloads most often when they are outaged. A Security Constrained Optimal Power Flow (SCOPF) is used to identify the main network impact of the randomly sampled conditions and analysis of the results is performed to distinguish the line overloads caused by renewable sources from those caused by demand and/or conventional generation and to identify the 110 kV network locations that are the best candidates for the new 220 kV (275 kV)/110 kV substations. All these results are further exploited in order to propose a list of the network reinforcements for each generation portfolio. The reinforcements are verified for a range of plausible dispatches.

The reinforced networks obtained from Task 1 for each generation portfolio are used as starting points for the Task 2 studies. These studies employ various AC load flow based voltage stability and optimisation techniques. Although the starting points obtained from Task 1are difficult to solve from the voltage/reactive power point of view it can be shown that only a small number of additional network reinforcements are identified in Task 2. These reinforcements are mainly related to additional reactive power compensation required to ensure the power flow convergence and voltage compliance of the Irish electricity system.

Task 2 therefore builds upon the results of the first pass and addresses voltage and reactive power conditions on the network including voltage stability. By means of advanced software for the assessment of voltage security, the effect on branch loading of reactive power and any additional reinforcements necessary for the management of system voltage are identified for the most onerous operational scenarios and for each generation portfolio.

All studies carried out in Task 1 and Task 2 are steady-state calculations; dynamic studies have not been carried out in this work-stream.

The main output of this work is a list of the network reinforcements caused by new renewable generation and their approximate costs.

The report contains seven sections and five appendices. Section 1 is an introduction. Section 2 describes fundamental study assumptions used throughout this work. Section 3 summarises the identified Task 1 network constraints for base case studies and N-1 contingency analysis, while Section 4 presents the results obtained for the Task 1 randomisation studies. In Section 5 a set of network reinforcements is proposed for each portfolio based on the Task 1 network analysis. Section 6 summarises the identified Task 2 network constraints for base case studies and N-1 contingency, while the next section refines the network reinforcements identified in Section 5 based on the Task 2 network analysis.

Appendix A contains a list of all 110 kV wind farm grid locations used for different generation portfolios. Appendix B summarises the network reinforcements between 2007 and 2020 that are envisaged by the transmission system operators. The network intact system MW flows for both winter peak and summer maximum operational regimes are given in Appendix C. Appendix D includes the network diagrams where the intact system and single contingency caused overloads are shown. Appendix E contains the results obtained for the Task 1 randomisation studies. Appendix F contains the lists of the network reinforcements obtained in the Task 1 work. Appendix G includes the finalised network reinforcements obtained through the Task 2 work. The last appendix includes the network drawing of the network reinforcements given in Appendix G.

2 Work-stream 3 Study Assumptions

In this section the assumptions that are used throughout the report are set out.

2.1 Demand

2.1.1. Three different operational (network) regimes have been employed throughout the work-stream 3 studies: winter peak, summer maximum and summer minimum. The total demand is: 9325 MW, 7372 MW and 3182 MW, for winter peak, summer maximum and summer minimum regimes respectively. The split between the NIE and Eirgrid electricity systems with respect to the total demand is shown in *Figure 2.1*. It should be pointed out that each of demand figures in *Figure 2.1* is a sum of individual MW consumption at the grid supply points. The grid MW losses are not taken into account in this figure, however the network losses are considered in the analysis.

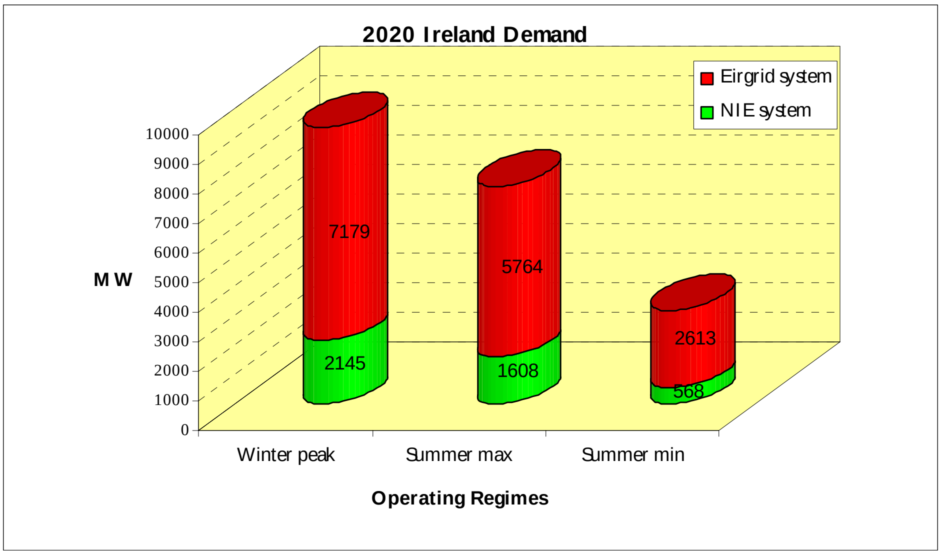

Figure 2.1- 2020 Ireland Demand

2.2 Generation

2.2.1. Generation used for the WS3 studies can be split into the following categories:

- conventional generating units,
- base renewable units,
- wind generation,
- variable renewable generation (wave and tidal).

The anticipated installed capacities are shown in *Figure 2.2* and *Table 2.1*.

Table 2.1 -2020 Generation Portfolios

	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A/6B
Conventional(MW)	9462	9192	9132	9302	8768	8346
Base renewable(MW)	150[1]	150[1]	150[1]	150[1]	328	360
Wind (MW)	2000	4000	4000	4000	6000	7982
Variable renewable(MW)	71	71	71	71	193	1593

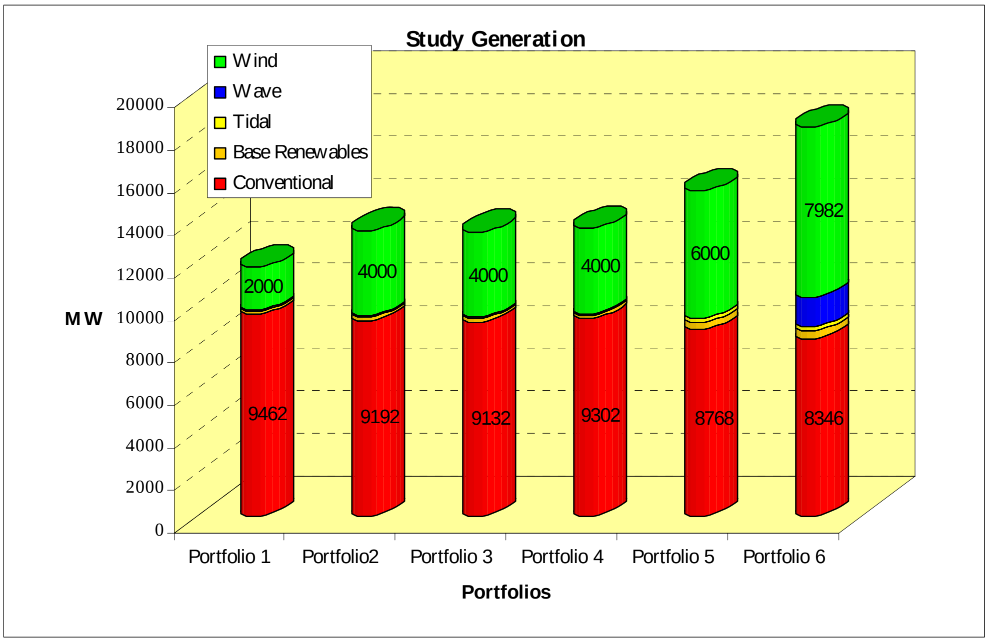

Figure 2.2 –Installed Generation Capacities for 2020Generation Portfolios

2.3 Conventional Generation

2.3.1. WS2a assumed that about 1.8 GW of the existing generating units would be retired by 2020. These units, their locations and capacities are given in the following table:

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[1] Not all grid locations for biogas generation were located by Work-stream 1(WS1). In this work only 15 MW out of 47MW of the proposed biogas generation by Work-stream 2a (WS2a) was used.

Table 2.2 -Retired generating units by 2020

Unit name	Unit code	Capacity (MW)	Location
TARBERT	TB1	54	South-West
TARBERT	TB2	54	South-West
TARBERT	TB3	240.7	South-West
TARBERT	TB4	240.7	South-West
AGHADA	AT1	90	South-West
AGHADA	AT2	90	South-West
AGHADA	AT4	90	South-West
NORTH WALL	NW4	163	Dublin
NORTH WALL	NW5	109	Dublin
POOLBEG	PB1	109.5	Dublin
POOLBEG	PB2	109.5	Dublin
POOLBEG	PB3	242	Dublin
GREAT ISLAND	GI1	54	South-East
GREAT ISLAND	GI2	54	South-East
GREAT ISLAND	GI3	108	South-East

2.3.2.The additional conventional capacities suggested by WS2a are amended by WS2b after running capacity adequacy studies. These additional conventional units are given in the following table:

Table 2.3- 2020 Additional conventional units

Type	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A/6B
	Unit(s)XSize(MW)					
Moneypoint Coal	.n.a.	n.a.	n.a.	3X387.5	n.a.	n.a.
CCGT	1X480 1X414 1X400	3x400	n.a.	3X400	3X400	3X400
OCGT	14X103.6	8X103.6	19X103.6	3x103.6	8X103.6	5X103.6
ADGT	1X89	5X107	5X107	n.a.	1X111	n.a.

2.4 Locations of new conventional units

2.4.1. The locations of new conventional units were not given in the work preceding WS3 and they needed to be determined. To determine these locations WS3 made the following assumptions:

A. Three new CCGT units to be connected at Whitegate (South-West), Aghada (South-West) and Huntstown (Dublin).

B. Some of the brown field sites from Table 1 to be utilised.

2.4.2. Assumption A is based on the following facts:

- In accordance with the latest Eirgrid Transmission Forecast Statement 2006-2012 Huntstown HN2 unit will be connected by the end of 2007.

- In accordance with the Commission for Energy regulation (CER) document “Agreement to Reduce ESB’s Market Share in the Power Generation Sector” and consultations with Eirgrid it is anticipated that two new CCGT units are likely to be connected in the Cork area at grid locations such as Whitegate and Aghada.

2.4.3. Assumption B is based on the following facts:

- It is assumed that with respect to the South-West region the brown field sites at Tarbert need to be utilised due to its closeness to fuel supply. However, it is assumed that only half of the existing capacity would be utilised due to a significant penetration of wind generation in the South-West region and the anticipated connection of the two new CCGT units in the Cork area (see the previous point 2.4.2).

- Considering that Great Island plant is the biggest plant in the South-East region it is assumed that this brown field site would need to be utilised. It should be pointed out that the existing Great Island units are HFO fuel type units, however it is assumed that gas pipes can be brought to this site.

- The Dublin area is the biggest demand centre and it is assumed that the brown field sites at Poolbeg 1, 2 and 3 would need to be utilised.

- It is assumed that the existing generation site at Kilroot (Northern Ireland) would able to accommodate up to 500MW of additional capacity with respect to the capacity suggested by WS2a.

2.4.4. Taking into account the assumptions discussed in the last two paragraphs it is assumed that the following sites can be utilised to accommodate the new conventional units suggested by WS2a:

Table 2.4 - Locations of new 2020 conventional units

Type	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A/6B
	Unit(s)XSize(MW)					
New Coal Units				Moneypoint 3x387.5 MW		
CCGTs	Whitegatex1 480MW Aghadax1 414MW Huntstownx1 400 MW	Whitegatex1 Aghadax1 Huntstownx1 All 400 MW		Whitegatex1 Aghadax1 Huntstownx1 All 400 MW	Whitegatex1 Aghadax1 Huntstownx1 All 400 MW	Whitegatex1 Aghadax1 Huntstownx1 All 400 MW
OCGTs	Poolbegx4 Great Islandx2 Tarbertx3 Kilrootx5 All 103.6 MW	Great Islandx2 Tarbertx3 Kilrootx3 All 103.6 MW	Aghadax3 Huntstownx4 Poolbegx5 Great Islandx2 Tarbertx3 Kilrootx2 All 103.6MW	Poolbegx2 103.6MW	Poolbegx3 Great Islandx2 Tarbertx3 All 103.6	Poolbegx3 Great Islandx2 All 103.6MW
ADGT	Poolbegx1 89 MW	Poolbegx5 All 107 MW	Whitegatex4 Aghadax1 107MW		Poolbegx1 111 MW	

2.4.5. It is assumed that the new CCGT units connected at Whitegate, Aghada and Huntstown are ‘positioned’ high in merit orders (likely to be committed first) while other new conventional units are ‘positioned’ low in the merit order lists.

2.5 Scheduling of conventional units

2.5.1. The scheduling of generating units for the WS3 Task 1 studies is based on the following facts:

- The number of scheduled conventional units or unit commitment depends on the net system demand, the required spinning reserve and the proposed merit order lists.
- The merit order lists are agreed with the Working Group. The units from the top of merit order list are committed first to meet both net demand and spinning reserve requirements.
- Having found which units have to be committed a simple optimisation procedure is run to determine the least cost economic dispatch.

2.5.2. The net demand is the sum of demand at all grid supply points offset by the total power output of renewables (wind, base and variable renewables).

2.5.3. The spinning reserve is the additional generation that needs to be available instantaneously in the case of sudden loss of generation or unexpected wind power output fluctuations. The spinning reserve requirements for the transmission system of the whole island consist of two parts: constant 'contingency' reserve and variable 'fluctuation' reserve required to cover unexpected wind fluctuations. The contingency reserve is required to match 80% of the largest unit MW capacity, and it is set at 320 MW in this study. The amount of primary (POR), secondary (SOR[2]) and tertiary (TOR[2]) reserve required to cover unexpected wind fluctuations vary with the total wind power output on the system. Considering that WS3 is a steady-state study of network conditions it is assumed that the study should focus on the TOR requirements. The spinning reserve requirements were already set by WS2b in its methodology report as follows:

Table 2.5 -Reserve requirements to cover unexpected wind fluctuations

Total wind power output for the whole island MW	POR MW	SOR MW	TOR MW
0	0	0	0
1000	1	2	5
2000	3	6	18
3000	4	12	37
4000	6	18	63
5000	8	27	94
6000	10	36	131
7000	13	48	174
8000	16	61	225

2.5.4. The Turlough Hill power station (292 MW total power output) is designated as the swing busbar for all operational regimes. The least cost economic dispatch does not take this plant into account, which means that the power output of Turlough Hill is assumed to be 0 MW in all studies.

2.5.5. It is assumed that the contingency reserve requirements will be shared between the Turlough Hill power station and all other units that can provide TOR. If the total wind power output for the transmission system of the whole island is 7000 MW the total reserve requirements are estimated to be 494 MW (320 MW and 174 MW, see *Table 2.5*). The Turlough Hill power station would then provide 292 MW of the required 494 MW. All other units will provide the difference of 494 MW and 292 MW, which is 204 MW. The use of interruptible load is not considered for the provision of reserve in this study.

2.6 Wind generation

2.6.1. The anticipated 2020 on-shore wind generation in Ireland is geographically spread over wind zones. The installed wind farm capacities for 110 kV nodes are given in *Appendix A*. The geographical spread of wind generation is shown in *Figure 2.3*. It can be seen that Ireland is split into several wind zones denoted by ROI_A to ROI_I for the Republic of Ireland, NI_A to NI_B for Northern Ireland and several offshore wind zone OS_A to OS_J(only the zones where some offshore wind farms are suggested by Work-stream 1 are shown in this figure). For each portfolio the total

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[2] These are cumulative figures, for example the TOR figures include POR and SOR figures.

installed capacities are shown, thus for example for Portfolio 1 (P1) the total installed wind capacity in the wind zone ROI_A is 262 MW. The highest penetration are anticipated in the South-West region (Wind zones: ROI_F and ROI_H), West-Midlands (ROI_B) and North-West (ROI_A and NI_B).

2.7 Base renewable generation

2.7.1. The base renewable generation includes biomass, biogas and landfill gas. The anticipated installed capacities are 150 MW for portfolios 1 to 4, 328 MW in Portfolio 5 and 360 MW in Portfolio 6A.

2.8 Variable renewable generation

2.8.1. Variable renewable generation includes tidal and wave generation.

2.8.2. The total installed capacity of tidal generation is 71 MW for portfolios 1 to 4 and 193 MW for portfolios 5 and 6. All units are located in Northern Ireland.

2.8.3. The total installed capacity of wave generation in Portfolio 6A/6B is 1.4 GW. The grid locations of these units are: Bellacorrick (448 MW), Galway (210 MW), Castlebar (224 MW), Oughtragh (406 MW) and Ballylickey (112 MW).

2.9 Network

2.9.1. It is assumed that a new 500 MW interconnector between the Eirgrid system and the England and Wales power system will be connected to Woodland 400 kV. The interconnector is split into two hypothetical generators. The first generator is 'positioned' high in the merit order lists while the second generator is 'positioned' low in the merit order lists. The same logic is applied to the Moyle interconnector. A new interconnector between Northern Ireland (Tyrone) and the Republic of Ireland (Cavan) is considered in the study.

2.9.2. Slack busbar is 220 kV Turlough Hill whose maximum MW generation is 4x73MW.

2.9.3. It is anticipated that the 220 kV network in the Cork region needs to be reinforced in order to accommodate the new conventional generation in this region (see *Table 2.4*). The suggested 220 kV network reinforcement is shown in *Figure 2.4.*The blue coloured lines in this figure are the new 220 kV lines, while the blue circle represent a new 220 kV substation. All of these are required to accommodate an addition of 800 MW of new conventional generation in this region.

2.9.4. The transmission system operators provided the network data used in this work. This data contains the envisaged network reinforcements between 2007 and 2020. These are the reinforcements required only due to anticipated load growth and conventional portfolio. They are listed in *Appendix B*.

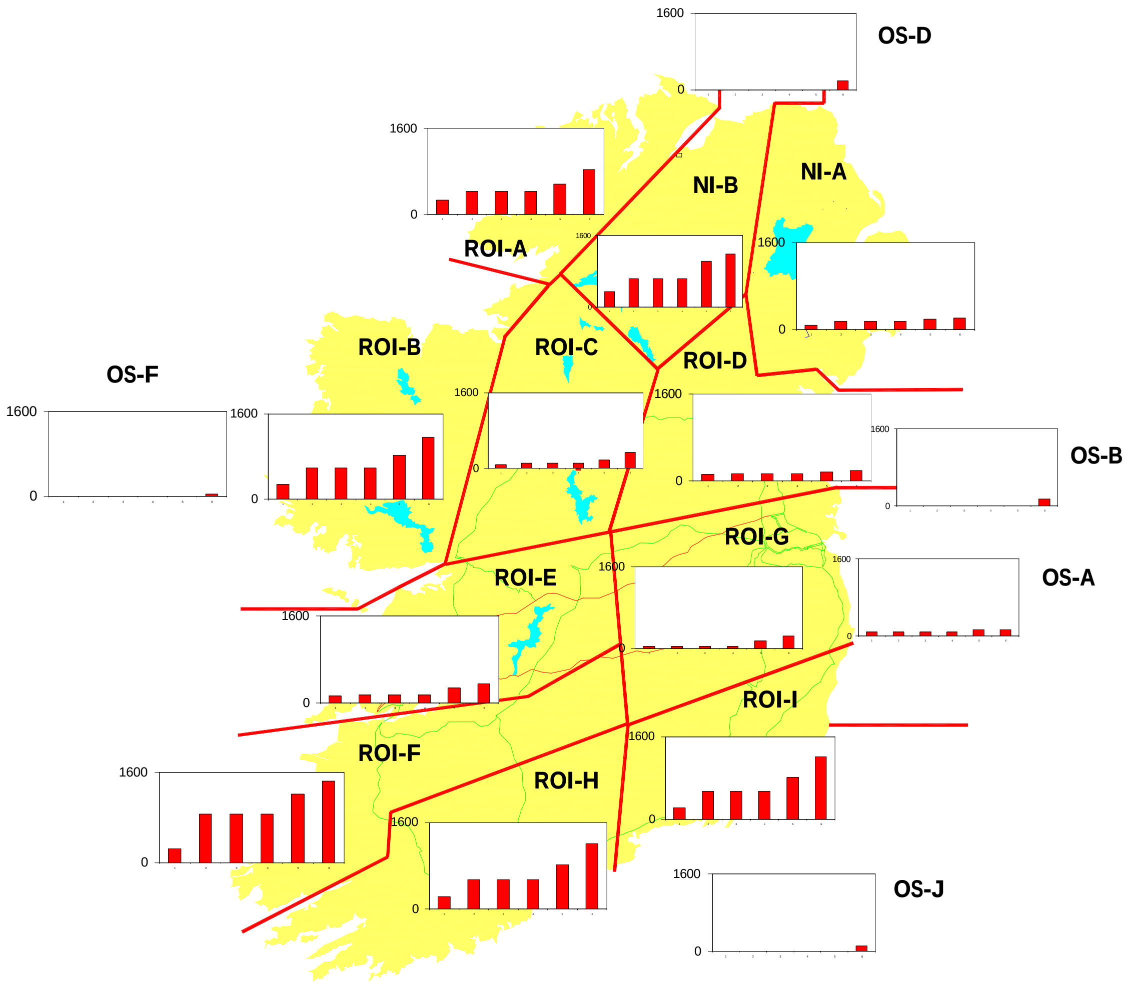

Figure 2.3- Wind zones and zonal wind installed capacities

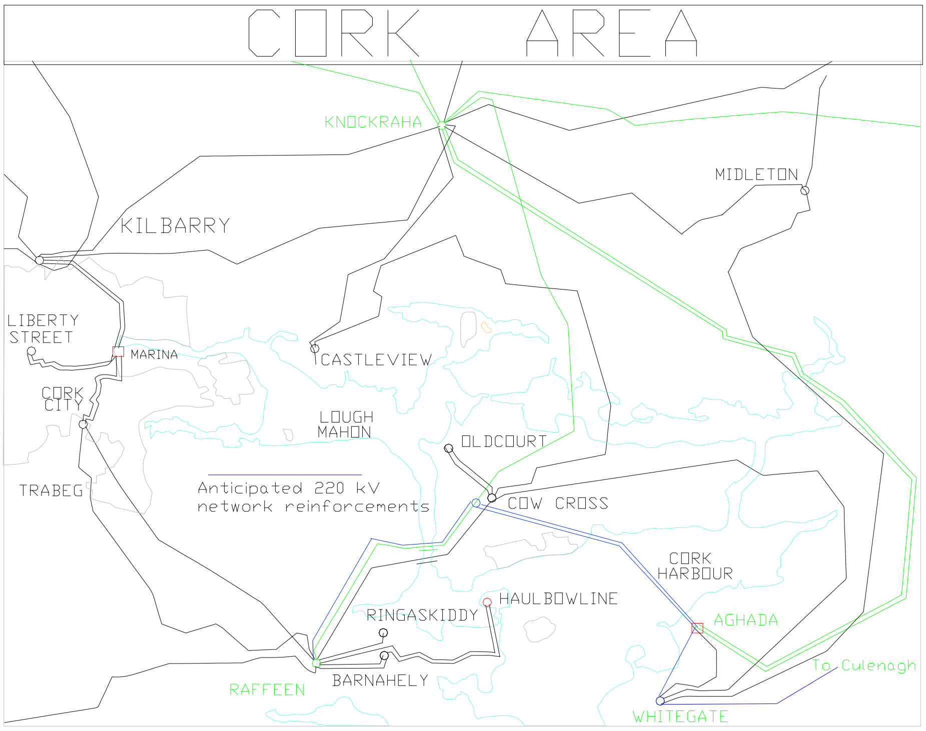

Figure 2.4 – Anticipated 2020 network reinforcement in the Cork area

3 Network Studies –Task 1

3.1. Base case DC load flow studies were carried out for winter, summer and summer minimum operational regimes.

3.1 Winter Peak Studies - Intact System

3.1.1. Two scenarios for the winter peak operational regime are created for these studies. In the first scenario the dispatchable conventional generation is maximised while in the second scenario the wind penetration is maximised. The MW flows are shown in *Appendix C* (figures *Figure C1*, to *Figure C6*) only for the second scenario.

3.1.1 Winter peak studies- maximised conventional generation

3.1.1.1. The winter peak studies are carried out using different wind scaling factors[3] for each portfolio. The wind scaling values are chosen to ensure that all conventional generating units are committed for each portfolio. The renewable generation and demand totals used for each portfolio are given in the following table:

Table 3.1-Base Case Winter Peak Studies –Intact System –All conventional units dispatched

	Portfolio1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
Wind Power Output (MW)	200	480	520	360	660	718
Other Renewables Power Output (MW)	180.6	180.6	180.6	180.6	409	896
Demand (MW)	9325	9325	9325	9325	9325	9325

3.1.1.2. The number of overloaded lines for different MW line rating correction factors [4] is given in the following table. It should be pointed out that the overloaded lines are identified for the intact system where contingencies are not taken into account.

Table 3.2-Number of overloaded lines – Winter Peak - Intact System - All conventional units dispatched

Number of overloaded lines	Portfolio1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
MW=MVA rating	7	2	2	9	2	3
MW=0.95*MVA rating	8	6	7	11	5	7
MW=0.9*MVA rating	10	9	8	11	6	7

3.1.1.3. The overloaded lines for the intact (no contingencies) winter peak operational regime are summarised for all portfolios in the following table (the applied MW line rating correction factor is 1.0).

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[3] Wind scaling factor is a percentage of the wind farm installed capacity. In this section the same scaling factor is used for each wind grid location in Ireland.

[4] DC load flow is used to calculate MW flows in this report. Considering that the line ratings are given in MVA, we applied MW line rating correction factors to take into account the MVAr flow contribution.

Table 3.3 –Overloaded lines/transformers –Winter Peak – Intact System - All conventional units dispatched

ID	Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating (MVA)	Max absolute flows(MW)	Maximum Loading (%)
1	3282	KILLONAN	-	220 kV transformer	120	129	107
2	3282	KILLONAN	-	220 kV transformer	63	64	102
3	3282	KILLONAN	-	220 kV transformer	63	65	103
4	4522	PROSPECT	5142	TARBERT	381	456	119
5	1401	BELLACORICK	1661	CASTLEBAR	126	126	100

Deleted: 5

3.1.1.4. The Killonan transformers (ID=1,2,3) are overloaded in Portfolio 1 and Portfolio 4 due to the increased power flows through the Limerick region and demand requirements at Nenagh and Ahane. The 220 kV line (ID=4) between Prospect and Tarbert is overloaded only in Portfolio 4 due to a significant power injection at Moneypoint (3 new coal units). The 110 kV line (ID=5) between Bellacorick and Castlebar is overloaded only in Portfolio 6A due to the injection of renewable power generation located at Tawnaghmore (biomass) and Bellacorick (wind and especially wave generation).

3.1.1.5. When applying MW line rating correction factors of 0.9 several additional lines given in the following table become overloaded:

Table 3.4 -Additional overloaded lines, correction factor 0.9- All conventional units dispatched

ID	Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating (MVA)	Max absolute flows(MW)	Loading (%)
1	1642	CASHLA	5172	TYNAGH	518	501.1	107
2	1741	CARRICKMINES	1801	COOKSTOW	143	137.9	107
3	1931	CUNGHILL	4981	SLIGO	126	120	105

3.1.2 Winter peak studies- maximised wind penetration

3.1.2.1. To make a preliminary assessment of the impact of high wind penetration on the line flows the wind penetration is maximised and the dispatchable conventional generation is minimised. The renewable generation and demand totals and the number of dispatched units used for each portfolio are given in the following table:

Table 3.5 - Base Case Winter Peak Studies –Intact System –Wind maximised

	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
Wind Power Output(MW)	2000	4000	4000	4000	6000	5986
Other Renewables Power Output(MW)	180.6	180.6	180.6	180.6	409	896
Demand (MW)	9325	9325	9325	9325	9325	9325
Number of dispatched units	55	41	48[5]	38	34	35[6]

3.1.2.2. It can be seen from the table above that Portfolio 6A cannot accommodate more than 5986 MW of wind generation and 896 MW of other renewable generation. The spinning reserve requirements discussed in Section 2 dictate the minimum number of dispatchable conventional units and therefore the maximum renewable penetration on the system.

3.1.2.3. Base case MW flows are shown in the drawings given in *Appendix C*, *Figure C1* to *Figure C6*. It should be pointed out that these flows are shown only for a set of single 110 kV and 220 kV circuits.

3.1.2.4. The number of overloaded lines for different MW line rating correction factors is given in the following table. It should be pointed out that the overloaded lines are identified for the intact winter peak regime where contingencies are not taken into account. The number of overloaded lines for the intact system is similar for Portfolios 2,3 and 4. On the other hand, the number of overloaded lines for Portfolio 6A is significantly larger even the total renewable penetration is only about 0.5 GW larger than in Portfolio 5. The reason behind such increase lies in the fact that there is a ‘knee’ point between 6.5 GW and 7GW of renewable power output. Any further increase in renewable power output after this ‘knee’ point leads to a rapid increase in the number of overloaded lines and consequently network reinforcement costs. The knee point is identified through contingency analyses of a significant number of randomly chosen operational scenarios that permit exploration of the impact of variability in renewable resources. These analyses will be discussed in the following sections.

Table 3.6- Number of overloaded lines – Winter Peak - Intact System – Wind maximised

Number of overloaded lines	Portfolio1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
MW=MVA rating	2	11	12	13	26	35
MW=0.95*MVA rating	5	13	15	15	32	40
MW=0.9*MVA rating	8	17	17	19	36	42

3.1.2.5. The results presented in the previous table show that even for the intact system a significant number of lines is overloaded in the last two portfolios.

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[5] It should be noted that Portfolio 3 is the only portfolio that has a significant number of small OCGT units, which caused a significant number of units to be dispatched.

[6] The total conventional power output is smaller in Portfolio 6 than in Portfolio 5, however the number of dispatched units is larger due to reserve requirements. A significant number of units in these two portfolios is running part loaded.

3.1.2.6. The overloaded lines for all portfolios are shown in *Appendix D Figure D1* to *Figure D6*). The overloaded lines for the intact system are highlighted by red colours.

3.1.2.7. It can be seen from *Appendix D* that a significant number of overloaded lines was found in the areas where significant wind resources are identified by Work-stream 1. These are:

- South-West.
- Co. Donegal,
- Co. Sligo and Co. Mayo,
- Northern Ireland (Omagh)
- East Coast (Arklow) in Portfolio 6A.

Portfolio 1

3.1.2.8. Apart from the 110 kV lines between Carrickmines and Pottery and Finglas Urban and McDermot any other overloaded lines were not identified for this portfolio for the intact system.

Portfolio 2

3.1.2.9. The most severely(>120% loading) overloaded lines in Portfolio 2 for the intact system are:

Table 3.7-Winter Maximum -Intact System - Overloaded Lines - Portfolio 2

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating(MVA)	MW flows	Overload (%)
1401	BELLACORICK	1661	CASTLEBAR	126	182	144
5141	TARBERT	5261	TRIEN	128	-201	157

Portfolio 3

3.1.2.10. The most severely (>120% loading) overloaded lines in Portfolio 3 for the intact system are:

Table 3.8- Winter Maximum -Intact System - Overloaded Lines - Portfolio 3

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating(MVA)	MW flows	Overload (%)
1401	BELLACORICK	1661	CASTLEBAR	126	180	143
5141	TARBERT	5261	TRIEN	128	-203	158

Portfolio 4

3.1.2.11. The most severely (> 120% loading) overloaded lines in Portfolio 4 for the intact system are:

Table 3.9-Winter Maximum -Intact System - Overloaded Lines - Portfolio 4

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating(MVA)	MW flows	Overload (%)
1401	BELLACORICK	1661	CASTLEBAR	126	179	142
5141	TARBERT	5261	TRIEN	128	-199	155

Portfolio 5

3.1.2.12. The most severely (>120% loading) overloaded lines in Portfolio 5 for the intact system are:

Table 3.10- Winter Maximum -Intact System - Overloaded Lines - Portfolio 5

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating(MVA)	MW flows	Overload (%)
1401	BELLACORICK	1661	CASTLEBA	126	261	207
1881	CHARLEVILLE	2881	GLENLARA	126	-170	135
1931	CUNGHILL	4041	MOY	126	-184	146
1931	CUNGHILL	4981	SLIGO	126	207	165
1981	CORRACLASSY	2821	GORTAWEE	126	161	128
2041	CORDUFF	3761	MACETOWN	143	175	123
3581	LETTERKENNY	9516	STRABANE PST	126	211	168
4481	PORTLAOISE	2419	DALLOW TEE	103	-126	122
4941	SHANNONBRIDGE	2419	DALLOW TEE	103	140	136
5141	TARBERT	5261	TRIEN	128	-234	183
75510	COOLKEERAGH	9510	STRABANE	166	-211	127
77010	DRUMNAKELLY	7510	DUNGANNON	103	-127	124
77010	DRUMNAKELLY	7510	DUNGANNON	103	-127	124
77510	DUNGANNON	7510	OMAGH	124	-218	176
77510	DUNGANNON	7510	OMAGH	124	-195	158
89510	STRABANE	9515	STRABANE PST	125	-211	169

Portfolio 6A

3.1.2.13. The most severely (>120% loading) overloaded lines in Portfolio 6A for the intact system are:

Table 3.11- Winter Maximum -Intact System - Overloaded Lines - Portfolio 6A

Bus 1 ID	Bus 1 name	Bus 2 ID	Bus 2 name	Ratting	MW flows	Overload (%)
1121	ARKLOW	4901	SHELTON ABBEY	57	-289	508
1401	BELLACORICK	1661	CASTLEBAR	126	309	245
1861	CARICKON	619	ARIGNA TEE	128	-153	120
1931	CUNGHILL	4041	MOY	126	-175	139
1931	CUNGHILL	4981	SLIGO	126	342	271

Table .12 cont- Winter Maximum -Intact System - Overloaded Lines - Portfolio 6A

Bus 1 ID	Bus 1 name	Bus 2 ID	Bus 2 name	Ratting	MW flows	Overload (%)
3581	LETTERKENNY	5361	TRILLICK	126	-206	164
3581	LETTERKENNY	9516	STRABANE PST	126	262	208
4361	OUGHTRAGH	3619	OUGHTRAGH TEE	126	211	167
4941	SHANNONBRIDGE	2419	DALLOW TEE	103	130	126
5141	TARBERT	5261	TRIEN	128	-200	156
75010	COLERAINE	4511	LOGUESTOWN	103	-138	134
89510	STRABANE	9515	STRABANE PST	125	-262	210

3.2 Summer Maximum Studies –Intact System

3.2.1. For summer operational regimes apart from the Turlough Hill plant the other hydro units are not dispatched. For summer maximum studies the wind penetration is maximised. The MW flows for this operational regime are shown in *Appendix C*, (*Figure C 7* to *Figure C 12*).

3.2.2. The renewable generation, demand totals, and the number of despatched units are given in the following table. It should be pointed out that the maximum power output in Portfolios 1,2,3 and 4 is basically the same as the installed wind capacity. On the other hand, in Portfolio 5 and Portfolio 6A only a certain percentage of the total installed wind capacity can be accommodated due to the reserve requirements discussed in *Section 2*. In Portfolio 6A there is 1.4 GW of wave generation which is treated in the same way as the wind generation with respect to the system reserve requirements. This is the main reason why the wind power output in Portfolio 6A is smaller than in Portfolio 5.

Table 3.12 - Base Case Summer Maximum Studies –Intact System –Wind maximised

	Portfolio1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
Wind Power Output (MW)	2000	4000	4000	4000	4800	4390
Other Renewables Power Output (MW)	180.6	180.6	180.6	180.6	409	897
Demand (MW)	7372.8	7372.8	7372.8	7372.8	7372.8	7372.8
Number of dispatched units	27	16	20	16	16	16

3.2.3. The number of overloaded lines for different MW line rating correction factors is given in the following table. It should be pointed out that the overloaded lines are identified for the intact summer maximum operational regime where contingencies are not taken into account.

Table 3.13-Number of overloaded lines – Summer Maximum - Intact System - Wind maximised

Number of overloaded lines	Portfolio1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
MW=MVA rating	2	17	23	17	22	23
MW=0.95*MVA rating	3	23	28	23	24	27
MW=0.9*MVA rating	4	27	29	27	29	33

3.2.4. It can be seen from the table above that for this operating regime a significant number of lines is overloaded even for the intact system when the wind penetration is maximised. Comparing these results to the ones presented in *Table 3.6* it can be seen that there is a significant increase in the number of overloaded lines for Portfolio 3.

3.2.5. The overloaded lines for all portfolios are shown in *Appendix D* (*Figure D7* to *Figure D12*). The overloaded lines for the intact system are highlighted by red colours.

3.2.6. It can be seen from *Appendix D* that a significant number of overloaded lines was found in:

- South-West region.
- Co. Donegal,
- Co. Sligo and Co. Mayo,
- Northern Ireland(Omagh),
- East coast (Arklow) in Portfolio 6A.

Portfolio 1

3.2.7. Apart from the 110 kV lines Bellacorick to Castlebar and Coolkeeragh to Lisaghmore other overloaded lines are not identified for the summer maximum studies (intact system) in Portfolio 1.

Portfolio 2

3.2.8. The most severely (loading >120%) overloaded lines in Portfolio 2 for the intact system are:

Table 3.14 -Summer Maximum -Intact System - Overloaded Lines - Portfolio 2

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating (MVA)	MW flows	Loading (%)
1401	BELLACORICK	1661	CASTLEBAR	107	190	178
1931	CUNGHILL	4981	SLIGO	107	139	129.5
2002	CULLENAGH	2742	GREAT ISLAND	229	299	130.5
3581	LETTERKENNY	89516	STRABANE PST	107	137	128.5
4941	SHANNONBRIDGE	22419	DALLOW TEE	72	88	122.2
5141	TARBERT	5261	TRIEN	120	-208	173.4
75510	COOLKEERAGH	84411	LISAGHMORE	82	-128	155.7
77510	DUNGANNON	87510	OMAGH	109	-136	124.7

Portfolio 3

3.2.9. The most severely (loading >120%) overloaded lines in Portfolio 3 for the intact system are:

Table 3.15 -Summer Maximum -Intact System - Overloaded Lines - Portfolio 3

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating (MVA)	MW flows	Loading (%)
1401	BELLACORICK	1661	CASTLEBAR	107	191.0	178.5
1601	CLASHAVOON	1611	CLONKEEN	187	-234.6	125.5
1931	CUNGHILL	4981	SLIGO	107	138.0	129.0
3581	LETTERKENNY	9516	STRABANE PST	107	133.6	124.9
4941	SHANNONBRIDGE	2419	DALLOW TEE	72	92	128.2
5141	TARBERT	5261	TRIEN	120	-195	162.1
75510	COOLKEERAGH	4411	LISAGHMORE	82	-128	155.7
77510	DUNGANNON	7510	OMAGH	109	-133	122.4

Portfolio 4

3.2.10. The most severely (loading >120%) overloaded lines in Portfolio 4 for the intact system are:

Table 3.16 -Summer Maximum -Intact System - Overloaded Lines - Portfolio 4

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating (MVA)	MW flows	Loading (%)
1401	BELLACORICK	1661	CASTLEBAR	107	190.5	178.1
1931	CUNGHILL	4981	SLIGO	107	138.5	129.5
2002	CULLENAGH	2742	GREAT ISLAND	229	298.8	130.5
3581	LETTERKENNY	9516	STRABANE PST	107	137.4	128.5
4941	SHANNONBRIDGE	2419	DALLOW TEE	72	87.9	122.2
5141	TARBERT	5261	TRIEN	120	-208.1	173.4
75510	COOLKEERAGH	4411	LISAGHMORE	82	-127.6	155.7
77510	DUNGANNON	7510	OMAGH	109	-135.9	124.7

Portfolio 5

3.2.11. The most severely (loading >120%) overloaded lines in Portfolio 5 for the intact system are:

Table 3.17 –Summer Maximum –Intact System – Overloaded Lines – Portfolio 5

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating (MVA)	MW flows	Loading (%)
1401	BELLACORICK	1661	CASTLEBAR	107	219.5	205.2
1881	CHARLEVILLE	2881	GLENLARA	107	-136.4	127.5
1931	CUNGHILL	4041	MOY	107	-162.1	151.5
1931	CUNGHILL	4981	SLIGO	107	181.1	169.3
3581	LETTERKENNY	89516	STRABANE PST	107	161.6	151.0
4481	PORTLAOISE	22419	DALLOW TEE	72	-91.2	126.7
4941	SHANNONBRIDGE	22419	DALLOW TEE	72	100.0	138.9
5141	TARBERT	5261	TRIEN	120	-176.1	146.8
77010	DRUMNAKELLY	77510	DUNGANNON	82	-102.9	125.6
77010	DRUMNAKELLY	77510	DUNGANNON	82	-102.9	125.6
77510	DUNGANNON	87510	OMAGH	109	-176.4	161.9
77510	DUNGANNON	87510	OMAGH	109	-157.8	144.8
89510	STRABANE	89515	STRABANE PST	125	-161.6	129.3

Portfolio 6A

3.2.12. The most severely (loading >120%) overloaded lines in Portfolio 6A for the intact system are:

Table 3.18 –Summer Maximum –Intact System – Overloaded Lines – Portfolio 6A

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Rating (MVA)	MW flows	Loading (%)
1121	ARKLOW	4901	SHELTON ABBEY	34	-221.1	650.5
1401	BELLACORICK	1661	CASTLEBAR	107	265.3	248.0
1931	CUNGHILL	4041	MOY	107	-164.6	153.9
1931	CUNGHILL	4981	SLIGO	107	292.1	273.0
3581	LETTERKENNY	5361	TRILLICK	107	-161.5	150.9
3581	LETTERKENNY	89516	STRABANE PST	107	203.6	190.4

Table 3.18cont- Summer Maximum –Intact System – Overloaded Lines – Portfolio 6A

Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Rating (MVA)**	**MW flows**	**Loading (%)**
4361	OUGHTRAGH	43619	OUGHTRAGH TEE	107	179.1	167.4
4481	PORTLAOISE	22419	DALLOW TEE	72	-91	126.5
4941	SHANNONBRIDGE	22419	DALLOW TEE	72	101.6	141.1
5141	TARBERT	5261	TRIEN	120	-147.1	122.6
75010	COLERAINE	84511	LOGUESTOWN	82	-113.9	138.9
89510	STRABANE	89515	STRABANE PST	125	-203.6	162.9

3.3 Summer Minimum Studies –Intact System

3.3.1. For these studies the wind penetration is maximised as much as possible, however the wind power output considered for these studies is significantly smaller due to a smaller system demand and the reserve requirements (see *Section 2*).

3.3.2. The renewable generation and demand totals, the number of dispatchable conventional units and wind power output used for each portfolio are given in the following table:

Table 3.19 - Base Case Summer Minimum Studies –Intact System –Wind maximised

	Portfolio1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
Wind Power Output (MW)	1400	1400	1400	1400	1200	400
Other Renewables Power Output (MW)	180	180	180	180	409	896
Demand (MW)	3182	3182	3182	3182	3182	3182

3.3.3. The number of overloaded lines for different MW line rating correction factors is given in the following table. It should be pointed out that the overloaded lines are identified for the intact summer minimum operational regime where contingencies are not taken into account. The results given in the table bellow show that the number of overloaded lines for the summer minimum studies is significantly smaller than for the winter peak and summer maximum operational regime.

Table 3.20-Number of overloaded lines – Summer Minimum Studies - Intact System - Wind maximised

Number of overloaded lines	Portfolio1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
MW=MVA rating	0	0	0	0	0	4
MW=0.95*MVA rating	1	1	0	0	0	4
MW=0.9*MVA rating	2	2	0	0	0	4

3.4 Contingency studies

3.4.1. N-1 contingency studies are carried out for all portfolios and both winter peak and summer maximum operational regimes.

3.4.1 N-1 contingency analysis - winter peak

3.4.1.1. The overloaded lines for all portfolios are shown in *Appendix D* (*Figure D1* to *Figure D6*).The overloaded lines for the intact system are highlighted by red colours while the overloaded lined caused by a single contingency are highlighted by blue colour.

3.4.1.2. The number of overloaded lines for each portfolio for the winter peak operational regime caused by a single contingency is given in the following table. It should be pointed out that the winter peak N-1 contingency studies assume the maximum possible wind penetration as given in *Table 3.5*. The lines that are overloaded for the intact system are **not** reported for the contingency studies.

Table 3.21 - Winter Peak - Number of overloaded lines

	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
Number of overloaded lines for the intact system	2	11	12	13	26	35
Number of overloaded lines caused by a single contingency	18	33	37	35	44	38

Portfolio 1

3.4.1.3. The most severely overloaded lines (loading >150%) in Portfolio 1 caused by a single contingency are:

Table 3.22- Winter Peak - Overloaded Lines - N-1 contingency analysis - Portfolio 1

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No[7]	Loading (%)
1401	BELLACORICK	1661	CASTLEBAR	123.6	199.8	126	12	158.6
1401	BELLACORICK	4041	MOY	76.3	199.8	126	1	158.6
1531	BALLYADA	5481	WHITEGATE	-101.8	192.4	126	2	152.7
1921	COW CROSS	5481	WHITEGATE	-90.6	209.4	126	3	166.2
1931	CUNGHILL	4981	SLIGO	68.6	192.1	126	1	152.5

3.4.1.4. The most onerous[8] single contingency is an outage of the 110 kV line Bellacorick to Castlebar.

Portfolio 2

3.4.1.5. The most severely overloaded lines in Portfolio caused by a single contingency are:

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[7] Number of times that the line found overloaded for all single contingencies.

[8] The most onerous contingencies are the ones that create the largest number of overloads.

Table 3.23 - Winter Peak - Overloaded Lines - N-1 contingency analysis - Portfolio 2[9]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1401	BELLACORICK	4041	MOY	33.8	215.9	126	1	171.4
1651	CLAHANE	5261	TRIEN	-36.4	238.0	126	1	188.9
1651	CLAHANE	5281	TRALEE	74.2	275.8	126	1	218.9
1931	CUNGHILL	4041	MOY	-106.2	288.4	126	1	228.9

3.4.1.6. The most onerous single contingencies are outages of the 110 kV lines Bandon to Dunmanway and Tarbert to Trien.

Portfolio 3

3.4.1.7. The most severely overloaded lines in Portfolio 3 caused by a single contingency are:

Table 3.24- Winter Peak - Overloaded Lines - N-1 contingency analysis - Portfolio 3[9]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1401	BELLACORICK	4041	MOY	35.6	215.9	126	1	171.4
1651	CLAHANE	5261	TRIEN	-34.9	238.0	126	1	188.9
1651	CLAHANE	5281	TRALEE	72.7	275.8	126	1	218.9
1931	CUNGHILL	4041	MOY	-108.1	288.4	126	1	228.9
2001	CULLENAGH	5441	WATERFORD	90.5	198.1	126	2	157.2

3.4.1.8. The most onerous single contingencies are outages of the 110 kV lines Bandon to Dunmanway and Tarbert to Trien.

Portfolio 4

3.4.1.9. The most severely overloaded lines in Portfolio 4 caused by a single contingency are:

Table 3.25 - Winter Peak - Overloaded Lines - N-1 contingency analysis – Portfolio 4[9]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1401	BELLACORICK	4041	MOY	36.4	215.9	126	1	171.4
1651	CLAHANE	5261	TRIEN	-38.4	238.0	126	1	189
1651	CLAHANE	5281	TRALEE	76.2	275.8	126	1	219
1931	CUNGHILL	4041	MOY	-108.9	288.4	126	1	229
2001	CULLENAG	5441	WATERFORD	91.6	202.5	126	2	161

3.4.1.10. The most onerous single contingencies are outages of the 110 kV line Bandon to Dunmanway and Tarbert to Trien.

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[9] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 3.7* – Portfolio 2, *Table 3.8* – Portfolio 3, *Table 3.9*– Portfolio 4.

Portfolio 5

3.4.1.11. The most severely overloaded lines in Portfolio 5 caused by a single contingency are:

Table 3.26 - Winter Peak - Overloaded lines - N-1 contingency analysis - Portfolio 5[10]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1401	BELLACORICK	4041	MOY	-32.1	240.0	126	3	190.5
1481	BUTLERSTOWN	2001	CULLENAGH	-112.3	195.0	126	2	154.8
1651	CLAHANE	5261	TRIEN	-7.5	242.0	126	1	192.1
1651	CLAHANE	5281	TRALEE	45.3	279.8	126	1	222.1
1881	CHARLEVILLE	3281	KILLONAN	94.4	186.6	103	5	181.2
1881	CHARLEVILLE	4021	MALLOW	85.3	179.7	103	2	174.5
2001	CULLENAG	5441	WATERFORD	122.1	239.7	126	16	190.2
3221	KILBARRY	4021	MALLOW	-92.2	186.6	103	2	181.2
5141	TARBERT	5281	TRALEE	-93.8	194.0	126	3	153.9
75510	COOLKEERAGH-	89510	STRABANE	-139.1	277.2	166	2	166.9

3.4.1.12. The most onerous single contingencies are outages of the 110 kV lines Bandon to Dunmanway, Tarbert to Trien, Bellacorick to Castlebar, Clashavoon to Clonkeen, Clashavoon to Knockraha, Letterkenny to Strabane, Tarbert to Trien and an outage of the 220 kV line Cullenagh to Great Island.

Portfolio 6A

3.4.1.13. The most severely overloaded lines in Portfolio 6A caused by a single contingency are:

Table 3.27 Winter Peak - Overloaded Lines - N-1 contingency analysis - Portfolio 6A[10]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1121	ARKLOW	4911	SHELTON	-2.8	292.3	103	1	283.8
1401	BELLACOR	4041	MOY	17.7	326.9	126	3	259.4
1601	CLASHAVOON	1611	CLONKEEN	-191.3	363.3	223	2	162.9
1641	CASHLA	2281	DALTON	-96.6	198.4	126	5	157.5
1651	CLAHANE	5281	TRALEE	-8.5	191.3	126	1	151.8
2521	FLAGFORD	4981	SLIGO	-121.7	211.7	126	15	167.9
2521	FLAGFORD	5341	TONROE	-94.5	220.8	126	4	175.2
5141	TARBERT	5281	TRALEE	-103.6	189.0	126	3	150.0
5281	TRALEE	43619	OUGHTRAGH	-172.0	363.3	223	1	162.9

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[10] The lines overloaded for the intact system are not included in this table. These lines are given in *Table 3.10*– Portfolio 5, *Table 3.11*- Portfolio 6A.

3.4.1.14. The most onerous single contingencies are outages of the 110 kV lines Bellacorick to Castlebar, Cunghill to Sligo, and Tarbert to Trien.

3.4.2 N-1 contingency analysis – summer maximum

3.4.2.1. The overloaded lines for the intact system are highlighted by red colours while the overloaded lined caused by a single contingency are highlighted by blue colour in *Figure D7* to *Figure D12* in *Appendix D*.

3.4.2.2. The number of overloaded lines for each portfolio for the summer maximum operational regime caused by a single contingency is given in the following table. It should be pointed out that the summer maximum N-1 contingency studies assume the maximum possible wind penetration as given in *Table 3.12*. The lines that are overloaded for the intact system are **not** reported for the contingency studies.

Table 3.28 –Summer Maximum - Number of overloaded lines

	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A
Number of overloaded lines for the intact system	2	17	23	17	22	23
Number of overloaded lines caused by a single contingency	22	35	25	35	34	43

Portfolio 1

3.4.2.3. The most severe (loading larger than 150%) overloaded lines in Portfolio 1 caused by a single contingency are:

Table 3.29 – Summer Maximum - Overloaded Lines - N-1 contingency analysis - Portfolio 1

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No[8]	Loading (%)
1401	BELLACORICK	1661	CASTLEBAR	123.6	199.8	126	12	158.6
1401	BELLACORICK	4041	MOY	76.2	199.8	126	1	158.6
1531	BALLYADA	5481	WHITEGATE	-101.7	192.4	126	2	152.7
1921	COW CROSS	5481	WHITEGATE	-95.8	208.9	107	5	195.3
1931	CUNGHILL	4041	MOY	-54.9	185.2	107	1	173.1
1931	CUNGHILL	4981	SLIGO	78.7	209	107	1	195.3

3.4.2.4. The most onerous single contingency is an outage of the 220 kV line Whitegate to Cullenagh.

Portfolio 2

3.4.2.5. The most severely overloaded lines in Portfolio 2 caused by a single contingency are:

Table 3.30– Summer Maximum - Overloaded Lines - N-1 contingency analysis - Portfolio 2[11]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1401	BELLACORICK	4041	MOY	26.8	217.3	107	2	203.0
1651	CLAHANE	5261	TRIEN	-24.6	232.7	107	1	217.5
1651	CLAHANE	5281	TRALEE	62.4	270.5	107	1	252.8
1881	CHARLEVILLE	4021	MALLOW	36.1	110.5	72	1	153.5
2001	CULLENAGH	5441	WATERFORD	69.4	162.1	107	2	151.5
5141	TARBERT	5281	TRALEE	-72.4	161.4	107	2	150.9

3.4.2.6. The most onerous single contingency is an outage of the 110 kV line Bandon to Dunmanway.

Portfolio 3

3.4.2.7. The most severely overloaded lines in Portfolio 3 caused by a single contingency are:

Table 3.31– Summer Maximum - Overloaded Lines - N-1 contingency analysis - Portfolio 3[11]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1401	BELLACORICK	4041	MOY	26.3	217.3	107	2	203.1
1651	CLAHANE	5261	TRIEN	-38.2	232.7	107	1	217.5
1651	CLAHANE	5281	TRALEE	75.9	270.5	107	1	252.8
1881	CHARLEVILLE	3281	KILLONAN	33.6	110.5	72	2	153.5

3.4.2.8. The most onerous single contingencies are outages of the 110 kV lines Tarbert to Trien and Clashavoon to Clonkeen.

Portfolio 4

3.4.2.9. The most severely overloaded lines in Portfolio 4 caused by a single contingency are:

Table 3.32– Summer Maximum - Overloaded Lines - N-1 contingency analysis - Portfolio 4[11]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No[7]	Loading (%)
1401	BELLACORICK	4041	MOY	26.8	217.3	107	2	203.1
1651	CLAHANE	5261	TRIEN	-24.6	232.7	107	1	217.5
1651	CLAHANE	5281	TRALEE	62.4	270.5	107	1	252.8
1881	CHARLEVILLE	4021	MALLOW	36.1	110.5	72	1	153.5
2001	CULLENAGH	5441	WATERFORD	69.4	162.1	107	2	151.5
5141	TARBERT	5281	TRALEE	-72.4	161.4	107	2	150.9

3.4.2.10. The most onerous single contingencies are outages of the 110 kV lines Tarbert to Trien and Bandon to Dunmanway.

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[11] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 3.14* – Portfolio 2, *Table 3.15* – Portfolio 3, *Table 3.16*- Portfolio 4.

Portfolio 5

3.4.2.11. The most severely overloaded lines in Portfolio 5 caused by a single contingency are:

Table 3.33– Summer Maximum - Overloaded Lines - N-1 contingency analysis - Portfolio 5[12]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1401	BELLACORICK	4041	MOY	-35.9	216.9	107	3	202.8
1651	CLAHANE	5261	TRIEN	-4.8	180.9	107	1	169.1
1651	CLAHANE	5281	TRALEE	35.1	211.2	107	1	197.4
1881	CHARLEVILLE	4021	MALLOW	67.6	152.2	72	5	211.5
2001	CULLENAGG	5441	WATERFORD	86.8	170.8	107	2	159.7
75510	COOLKEERAGH	89510	STRABANE	-108.9	217	144	1	150.7

3.4.2.12. The most onerous single contingencies are outages of the 100 kV lines Tarbert to Trien and Bellacorick to Castlebar.

Portfolio 6A

3.4.2.13. The most severely overloaded lines in Portfolio 6A caused by a single contingency are:

Table 3.34– Summer Maximum - Overloaded Lines - N-1 contingency analysis - Portfolio 6A[12]

Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Base MW flows	Max flows (MW)	Rating (MVA)	No	Loading (%)
1121	ARKLOW	4911	SHELTON	-2.1	223.3	72	1	310.1
1401	BELLACORICK	4041	MOY	17.8	283.2	107	3	264.7
1601	CLASHAVOON	1611	CLONKEEN	-147.6	291.1	187	1	155.7
1641	CASHLA	2281	DALTON	-87.9	174.8	107	5	163.7
1661	CASTLEBAR	5341	TONROE	103.5	211.3	137	4	154.2
1701	CATHALEEN'S FALL	1981	CORRACLASSY	103.9	180.7	107	15	168.9
2521	FLAGFORD	4981	SLIGO	-99.1	176.4	107	13	164.9
2521	FLAGFORD	5341	TONROE	-80.7	188.6	107	5	176.2
4981	SLIGO	5041	SRANANAGH	74.3	170.6	107	3	159.4
5281	TRALEE	43619	OUGHTRAGH TEE	-143.6	291.2	187	1	155.7
75010	COLERAINE	84512	LOGUESTOWN	-19.8	133.7	82	1	163.0
77510	DUNGANNON	87510	OMAH	-108.8	167.0	109	67	153.2

3.4.2.14. The most onerous single contingencies are outages of the 110 kV lines Bellacorick to Castlebar and Tralee to Oughtragh Tee.

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[12] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 3.17* – Portfolio 5, *Table 3.18* –Portfolio 6A.

3.5 Demand and renewable power curtailments

3.5.1. It is well known that line MW flows can be changed by increasing/decreasing the corresponding nodal power injections. The following nodal power injections are considered in this paragraph:

- nodal power injections of conventional units (positive);
- nodal negative power injections at the grid demand points and
- nodal renewable power injections (positive).

3.5.2. It is known that not all nodal power injections contribute equally to line flows and the contribution of individual injections to a particular line flows can be determined using a simple sensitivity analysis. The objective of this section is to look at the identified line overloads in more depth to distinguish the overloads caused by renewable power injections and the overloads caused by either demand negative injections or conventional unit power injections. It should be pointed out that it is not always possible to make such distinction and in some cases the injection discussed above contribute similarly to a particular line flow.

3.5.3. To accomplish this task a Security Constrained Optimal Power Flow (SCOPF) is used. The objective of such SCOPF is to ensure N-1 security using least cost control actions. An exercise called ‘reinforce nothing’ is carried out using SCOPF to demonstrate what would happen if the network cannot be reinforced and the only control possibilities are load and wind curtailment and generation output change. The objective of this exercise is to:

i. distinguish the line overloads caused by renewable sources and those caused by demand and/or conventional generation,

ii. identify the ‘contribution’ of individual renewable sources to the identified line overloads,

iii. summarise the results obtained for the different line overloads to identify 110 kV network locations that are the best candidates for new 220 kV/275 kV stations. The 110 nodes where a significant wind power curtailment is identified for many overloaded lines are such candidates.

3.5.4. SCOPF is an optimisation procedure where both renewable and load curtailment are treated as expensive control actions which can be used only when re-dispatching of the conventional units cannot ensure N-1 security. For a chosen operating regime and for all six portfolios both minimum renewable generation and load curtailment are determined in order to make sure that both intact system overloads and overloads caused by the most onerous single contingency are eliminated. The results related to the most onerous operational regimes will be discussed:

- summer maximum operational regime is chosen for the first four portfolios,
- winter peak operational regime is chosen for the last two portfolios.

3.5.5. These curtailments are summarised for the identified overloads and grouped on a regional basis. The main conclusion are given at the end of this section for each portfolio and several regions.

3.5.6. The best candidates for new 220 kV substations can be listed in the following order:

1. Bellacorick
2. Cunghill
3. Castlebar
4. Omagh
5. Letterkenny
6. Trillick

7. Sorne Hill
8. Coomagearlahy
9. Clonkeen
10. Charleville
11. Glenlara
12. Oughtragh
13. Macroom

3.5.7. The results of the ‘reinforce nothing’ exercise clearly show which nodal wind injections cause line overloads, and this then makes it possible to identify the overloads not directly caused by wind generation. Thus, for example the overloads of certain centrally located lines such as the 110 kV line Portlaoise to Dallow Tee, the 110 kV line Shannon Bridge to Dallow Tee (and Ikerin Tee), the 220 kV lines Cashla to Tynagh and Tynagh to Old Street are not directly caused by wind generation (there is almost no impact of nodal wind power injection on their line flows).

Portfolio 1

- The SCOPF results demonstrate that wind curtailment at Bellacorick, Moy and Cunghill is required to eliminate overloads of the following 110 kV lines: Bellacorick to Castlebar, Bellacorick to Moy, Cunghill to Sligo, Cungil to Moy.

- The overload of the 220 kV line between Cullenagh and Great Island can be eliminated by re-dispatching conventional units. The overload of 110 kV lines Great Island to Kilmurry and Kilmurry to Kellis can be eliminated by load curtailment at Kilmurry and Kellis.

- The overloads of the 110 kV lines in the Cork region (Ballyadam to Whitegate and Ballyadam to Middleton, Cow Cross to Whitegate) can be eliminated by re-dispatching the committed conventional units. For the 110 kV lines between Rafeen and Trabeg some additional load curtailment at Trabeg is required to eliminate the line overloads.

- The overloads of 110 kV lines in Dublin region can be eliminated by some load curtailment at Wolfetown, Artane, Cabra, Blackrock and Pottery.

- The overloads of 110 kV line between Shannonbridge and Ikerrin Tee can be eliminated by some load curtailment at Lisheen, Ikerrin and Thurles.

- In Northern Ireland, the overloads of 110 kV lines between Ballylumford and Eden can be eliminated by some demand curtailment at Eden and Carnmoney. Overload of the 110 kV lines between Coolkeeragh and Lisaghmore can be eliminated by some wind curtailment at Lisaghmore.

- The overloads of the 220 kV lines Cashla to Tynagh and Tynagh to Oldstreet can be eliminated by re-dispatching the committed conventional units.

Portfolios 2, 3 and 4

- The identified overloads of the 110 kV lines: Bellacorick to Castlebar, Bellacorick to Moy, Cunghill to Moy, and Cunghill to Sligo can be eliminated by some renewable power curtailment at Bellacorick, Moy, Tawnaghmore and Cunghill.

- A significant number of overloads is found in South-West region. The SCOPF results show that these overloads can be eliminated by wind curtailment in this region, especially wind curtailment at Coomagearlahy, Trien, Glanlee, Macroom, Athea, Coomacheo, Glenlara, Charleville. For some of these lines connected to Coolroe and Killbarry some demand curtailment is required at Coolroe.

- The overloads of 110 kV lines in Waterford and Wexford counties can be eliminated by demand curtailment. It should be pointed out that for some overloads (for example the 220 kV line Cullenagh to Great Island) wind curtailment in the South-West region is beneficial.

- Overloads of the 110 kV lines: Corraclassy to Gortawee, Letterkenny to Strabane, Coolkeeragh to Strabane and Strabane phase shifter transformers can be eliminated by wind curtailment at Letterkeny, Sorne Hill, Lisaghmore and Trillick.

- Overloads of the 110 kV lines Dungannon to Omagh and Drumnakelly to Dungannon can be eliminated by wind curtailment at Omagh.

- Overloads of the 110 kV lines connected to Dallow Tee can be eliminated by load curtailment at Portlaoise, Newbridge, Athe, Thornsberry.

- Overloads of the 110 kV lines between Finglas Urban and McDermot can be eliminated by load curtailment at Wolfetown and Cabra.

- Most of the conclusions stated in this paragraph are valid for Portfolio 2, Portfolio 3 and Portfolio 4.

Portfolio 5 and 6A

- The SCOPF results demonstrate that all overloads in Mayo and Sligo counties can be eliminated by wind curtailment at Moy, Tawnaghmore, Cunghill and Bellacorick. A significant wind curtailment at these nodes is required to eliminate overloads at the following 110 kV lines: Bellacorick to Castlebar, Bellacorick to Moy, Cunghill to Sligo, Flagfrod to Sligo, Flagford to Tonroe, Castlebar to Dalton, Castlebar to Cloon. In Portfolio 6A additional wind curtailment is required at Arigna, Binbane and Corderry to eliminate the overloads of the 110 kV lines: Carrick on Shannon to Arigna Tee, Flagford to Lanesboro, Flagford to Sligo, Arva to Carrick on Shannon, Corderry to Arigna Tee.

- A significant number of overloads is found in South-West region in Portfolio 5 and Portfolio 6A. The SCOPF results show that these overloads can be eliminated by wind curtailment in this region, especially wind curtailment at Coomagearlahy, Glanlee, Coomacheo (the lines connected to Clonkeen and Tralee and some impact on the lines connected to Tarbert), Athea, Trien (the 110 kV lines connected to Clahane and Tralee), Glenlara, Charleville and Mallow (the 110 kV line connected to Charleville). In Portfolio 6A a significant wave generation is curtailed at Oughtragh to help eliminate the overload of the following 110 kV lines: Clashavoon to Clonkeen, Clashavoon to Macroom, Tarbert to Trien, Oughtragh to Oughtragh Tee, and Tarbert to Tralee. For some of these lines connected to Coolroe and Killbarry some demand curtailment is required at Coolroe.

- Wind curtailment in counties Donegal and Tyrone, especially at Omagh, Letterkenny, Sorne Hill, Golagh, Enniskilen and Trilick is required to eliminate overloads of the following 110 kV lines: Cathallen’s Fall to Corraclassy, Cathalleen’s Fall to Srananagh, Corraclassy to Gortawee, Letterkenny to Strabane, Coolkeeragh to Strabane, Drumnakelly to Dungannon, Dungannon to Omagh, Strabane phase shifter transformer.

- Overloads of the 110 kV lines Shannonbridge to Dallow Tee and Dallow Tee to Portlaoise can be eliminated by load curtailment at Portlaoise, Newbridge, Dallow, Athy, and Thornsberry.

- Some demand curtailment at Mullingar is required to eliminate the overload of the 110 kV line between Lanesboro and Mullingar.

- Both wind and demand curtailments are required at Ballydine and Waterford to eliminate the overloads of the 110 kV line between Great Island and Waterford. Some demand curtailment is required at Kilmurry and Kellis to eliminate the overloads of the 110 kV line Great Island to Kilmurry. The same demand curtailment is beneficial for the elimination of the overload of the 110 kV line between Kilmurry and Kilkenny.

- A significant amount of wind curtailment is required at Shelton in Portfolio 6A to eliminate the overloads of the following 110 kV lines: Arklow to Shelton, Ballybeg to Charlesland, Charlesland to Carrickmines, Arklow transformers.

4 Randomisation Studies –Task 1

4.1. The main objective of the randomisation studies is to assess the impact of different generation scenarios on the network constraints. The generation scenarios are randomly created and their focus is on the wind power geographical distribution.

4.2. In the previous sections the focus was on the following two referent scenarios:

i. Winter peak – maximised wind
ii. Summer maximum – maximised wind

For both scenarios the wind power output is proportionally scaled across the whole country with respect to the installed capacities. Thus, for example for the summer maximum operating regime in Portfolio 6A the considered wind power output was 4160 MW out of 7982 MW installed capacity. For this scenario the power output of each individual wind farm is scaled using a factor of 4160/7982. Therefore, for the referent scenarios it is assumed that the same scaling factor is applied to the whole island (*all- island scaling*).

4.3. The randomisation process is based on the statistical analysis of 2004 wind power outputs in Ireland[13]. The whole island is split into several wind zones and only those wind farms that belong to the same wind zone can have the same scaling factor. In general, scaling factors are different for different wind zones (*zonal scaling*). Therefore, one of the most important features of the proposed randomisation process is a shift from *all-island scaling* to *zonal scaling*, or a shift from the assumption that the power output of all wind farms in Ireland are fully correlated to the assumption that only the power outputs of the wind farms from the same wind zone are fully correlated. Other characteristics of this randomisation process can be summarised as follow:

i. A set of random trials is created using a random number generator. Each trial is a set of 11 numbers and each number is associated with a wind zone. The random trials are created through a forced randomisation process where random numbers are repetitively generated until a wind zone correlation matrix similar to the one given in *Table 4.1* is obtained. To ensure that a good coverage of the problem space the minimum number of trials is set not to be smaller than 8,000.

ii. A number x_i from a trial is a uniform random number that represents the probability that wind power output of the i^{th} wind zone will not exceed CF_i percents of the total installed capacity of the zone. Using these numbers and cumulative frequency curves for the wind zones a zonal wind scaling factor can be calculated. For example, in *Figure 4.1* for a uniform random number $x_i = 0.6$the corresponding zonal wind scaling factor is CF_i= 26%. The cumulative frequency curves for each wind zone are obtained from a comprehensive 2004 statistical analysis of wind farm power output in Ireland.

iii. Random outages of the conventional units were included in these simulations: however the number of these units out of service was limited on a regional basis. When a unit is out of service that means the next available unit from the merit order list will be used instead. From the network analysis point of view this mean that economic dispatches have to be changed. The random outages of the conventional units are therefore further investigated in the post reinforcements stage when the proposed network reinforcements are verified against various dispatches for the most onerous wind power distribution scenarios identified here.

Table 4.1- Wind zone correlations[13]

	ROI_A	NI_B	NI_A	ROI_B	ROI_C	ROI_D	ROI_E	ROI_G	ROI_F	ROI_I	ROI_H
ROI_A	1.00	0.81	0.81	0.82	0.85	0.71	0.42	0.71	0.63	0.56	0.54
NI_B		1.00	0.87	0.83	0.89	0.77	0.46	0.77	0.65	0.62	0.60
NI_A			1.00	0.72	0.77	0.69	0.41	0.69	0.58	0.59	0.56
ROI_B				1.00	0.87	0.67	0.58	0.67	0.74	0.61	0.67
ROI_C					1.00	0.74	0.46	0.74	0.74	0.64	0.67
ROI_D						1.00	0.34	1.00	0.59	0.55	0.57
ROI_E							1.00	0.34	0.39	0.37	0.39
ROI_G								1.00	0.59	0.55	0.57
ROI_F									1.00	0.61	0.76
ROI_I										1.00	0.72
ROI_H											1.00

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[13] The wind data used for this analysis are taken from "Absorption of Renewable and Embedded Generation into Electricity Grids", PhD Thesis by Leslie Bryans, Queen's University, Belfast, 2006.

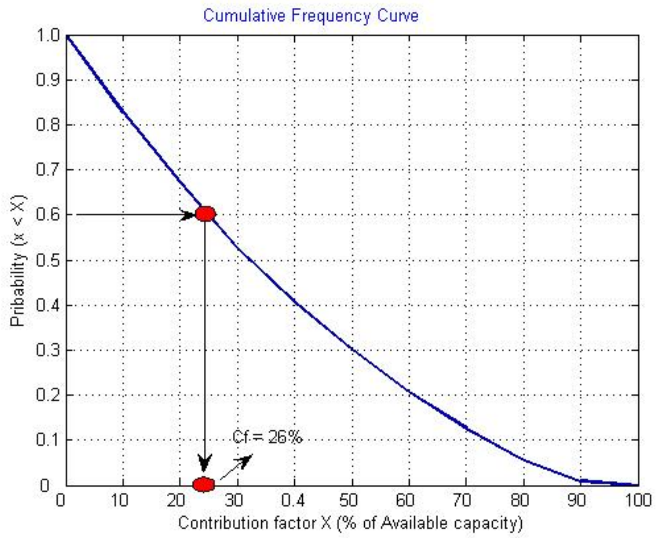

Figure 4.1 – Cumulative wind frequency curve[13]

4.4. Using SCOPF the 'reinforce nothing' exercise described above was conducted for each trial to determine the minimum load and wind curtailment that can guarantee that the system is N-1 secure with respect to the most onerous single contingencies. The load and wind curtailment recorded for each trial are clustered into bins and shown in *Figure 4.2*. The following conclusions can be made from this figure:

i. For all portfolios the largest number of trials belongs to the bin that is associated with the smallest ranges of wind and demand curtailment.

ii. The most onerous trials are mostly associated with the synchronised occurrence of large scaling factors in the zones with a significant wind installed capacities.

iii. It can be observed that wind and demand curtailment is bigger for the larger wind penetrations. Thus, in Portfolio 2 the maximum wind curtailment is about 500 MW for only a few trials, while in Portfolio 5 the maximum load curtailment is more than doubled (with respect to Portfolio 2) for a few trials.

iv. The minimum amount of wind and demand curtailment observed in Portfolio 6A are extremely high and this seems to be caused mainly by the addition of 1.4 GW of wave generation in the regions that are already heavily constrained.

v. It should be pointed out that Portfolio 6A is the only portfolio where all available wind power cannot be fully exploited due to spinning reserve requirements. It should be noted that 6GW of wind power out of 8GW of the installed capacity and about 900 MW of other renewables can be considered for the winter peak operational regime due to the spinning reserve requirements (see Section 2). Analysing the Portfolio 6A trials that have more than 6.9 GW and no spinning reserve requirement it is found that the number of network constraints and the wind and demand curtailment are significantly larger than for example for Portfolio 5.

vi. Further in-depth analysis of such trials suggest that, for renewable penetrations larger than 6.9 GW, the number of overloads was in many cases almost doubled with respect to Portfolio 5. Basically, for such trials the network reinforcement problem becomes more a network redesign problem and the network reinforcement techniques that will be discussed in the following section are found to be unsuccessful. For the sake of consistency (spinning reserve requirements) and the validity of the proposed network reinforcement techniques only up to 6.9 GW of renewable power output for the Irish system is therefore considered in this work.

vii. One of the most important conclusions from the randomisation studies is the identification of the system ‘knee point’, which is close to 6.9 GW of renewable power penetration. The extent of the network reinforcements for the penetrations larger than this ‘knee point’ can be rapidly enlarged.

4.5. The other results of these randomisation studies are related to the identification of:

i. frequently overloaded lines and

ii. lines whose outages frequently cause overloads.

4.6. For each portfolio and for each operational regime two tables are given in *Appendix E*. The first table contains lines sorted in ascending order with respect to the number of trials that a particular line is being significantly (> 150% loading, denoted by “>>”) or just overloaded (>105% loading, denoted by “>”). The second table contains lines sorted in ascending order with respect to the number of trials in which they caused other lines to be significantly (> 150%, denoted by “>>”) or just overloaded (> 105% and < 150%, denoted by “>”).

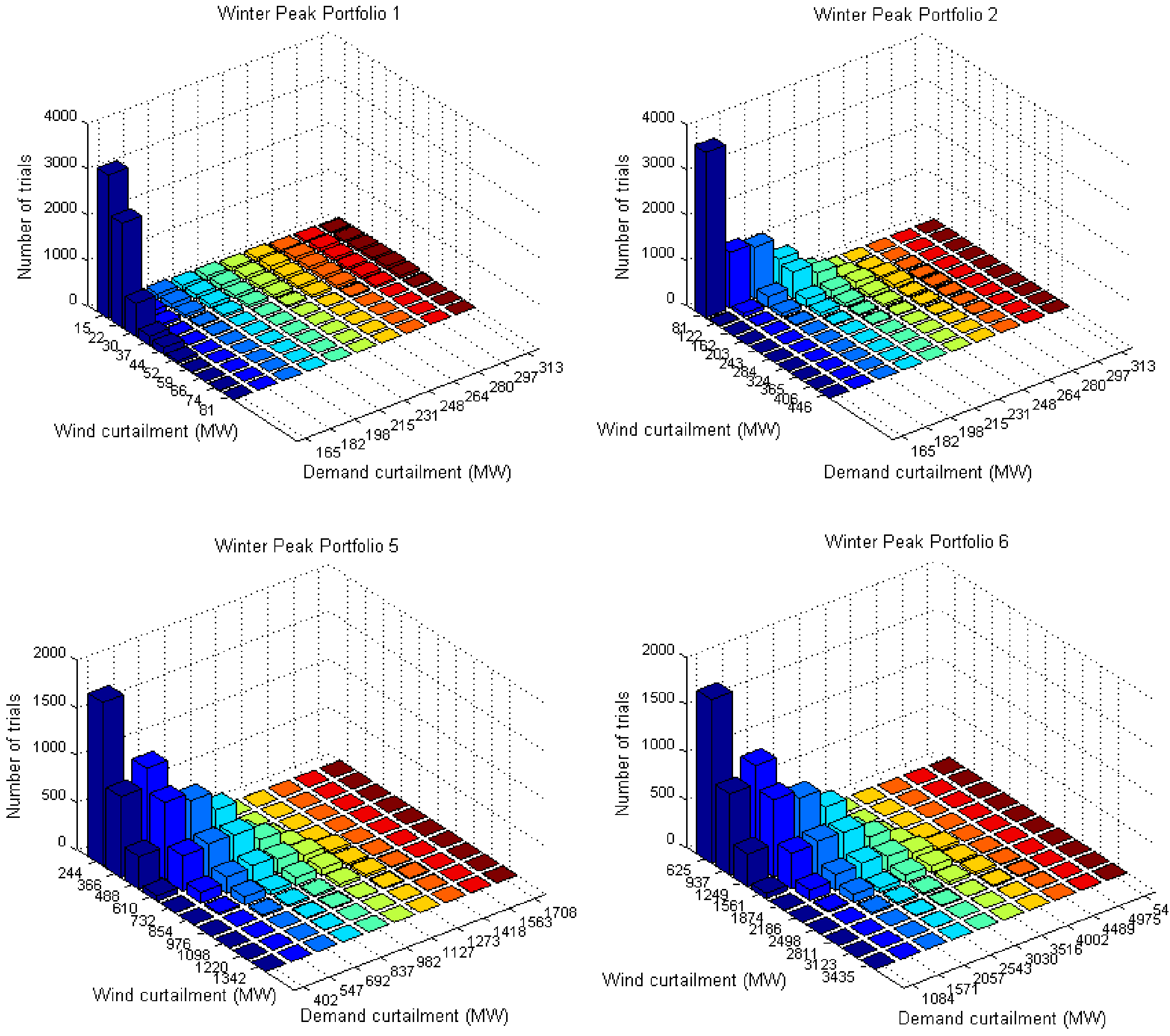

Figure 4.2 - Wind and demand curtailment – Statistics

5 Network Reinforcements – Task 1

5.1. It should be emphasised that the network reinforcements proposed in this section are:

- not all required reinforcements that will guarantee N-1 security of the Irish electricity system under all circumstances;
- the reinforcements that can eliminate only the identified network constraints caused by renewable generation which is basically the main objective of WS3 study.

5.2. The proposed reinforcements will be refined through Task 2. The voltage and reactive power related reinforcements will be identified in Task 2 as well.

5.3. Using the knowledge gained through randomisation process discussed in *Section 4* several areas are found where significant network reinforcements could be required. These areas are given in the priority order as follows:

1. Sligo and Mayo
2. Donegal and Northern Ireland
3. South-West
4. East Coast- Shelton and Arklow area
5. Cullenagh area.

5.4. Using the knowledge gained through the 'reinforce nothing exercise' (see *Section 3.5*) a set of possible grid locations for new 220 kV substations is determined.

5.5. The network flow diagrams shown in *Appendix C* clearly show that an increase in the renewable penetration in certain areas cause a significant loading of the 110 kV grid in the same areas and more importantly a significant de-loading of the 220 kV lines in the same areas. An example is the 220 kV ring in the South-West (see line flows for different portfolios in *Appendix C*). It will be clear in the next few paragraphs that one of the most important objectives of the proposed reinforcements is to "shift" a portion of wind to the 220/275 kV network, increase the loading of 220/275 kV network and decrease the loading of 110 kV network.

5.6. The network reinforcement carried out in Task 1 is an 'incremental' network reinforcement approach which consists of 'backward' and 'forward' phase (see *Figure 5.1*). The former phase starts with Portfolio 6A and identify all necessary network reinforcements for this most onerous portfolio. The required reinforcements for less onerous portfolios are determined removing one by one reinforcements from the previous step. The 'forward' phase identifies firstly all necessary reinforcements for the least onerous portfolio. The required reinforcements for more onerous portfolios are determined adding one by one reinforcement. A set of necessary network reinforcements was then found from these two phases.

5.7. Having found necessary network reinforcements an automation phase is then carried out relaxing one by one of these network reinforcements and repetitively running N-1 contingency analysis until the minimum level of network reinforcements is achieved.

5.8. The proposed network reinforcements are verified for various dispatching snapshots, for example:

- summer minimum WS2b snapshots - having only 6 conventional units dispatched and ignoring the spinning reserve requirements discussed in *Section 2*;
- minimum net demand snapshots resulted from the WS2b unit commitment studies- having 4.8 GW of demand (3.8 GWa nd 1 GW export to the UK), 1.4 GW of conventional generation, 3.2 GW of wind generation and 0.2 GW of other renewable generation and ignoring the spinning reserve requirements discussed in Section 2.

5.9. Many different random economic dispatches are run for the summer maximum and winter peak operational regimes creating various unit combinations and economic dispatch snapshots to verify the proposed network constraints.

5.10. The network reinforcements are given for Portfolio 6A, Portfolio 5, Portfolios 2, 3 and 4, and Portfolio 1. The main characteristics of the proposed network reinforcements are given in *Appendix F*.

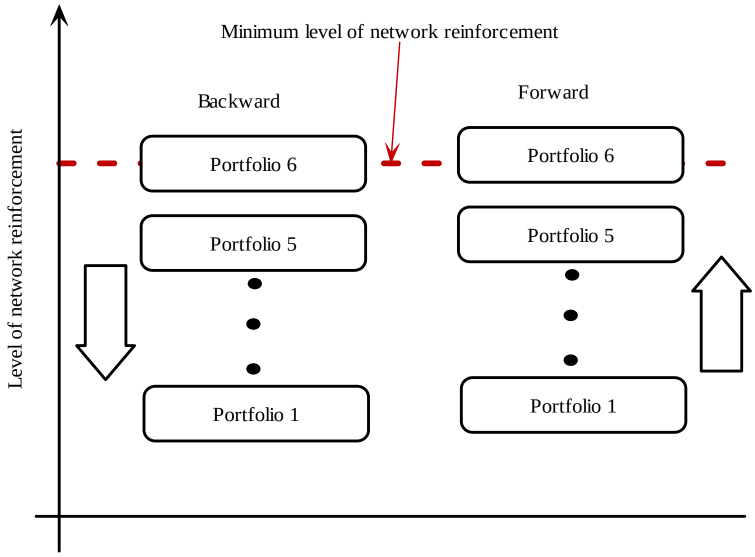

Figure 5.1 -Network reinforcement approaches

5.11. It should be pointed out that the network reinforcements proposed above for all portfolios do not ensure N-1 security considering that there is a number of lines which can be overloaded up to 10% for a single outage. In addition there are certain overloads even larger than 110% but those are not directly caused by renewable generation. The SCOPF studies for example show (see *Section 3.5*) that the overloads of the centrally located lines (the 110 kV line Portlaoise to Dallow Tee, the 110 kV line Shannon Bridge to Dallow Tee (and Ikerin Tee), the 220 kV lines Cashla to Tynagh and Tynagh to OldStreet)are not directly caused by wind generation (there is almost no impact of wind power injection on their line flows). Such overloads are summarised in the following table:

Table 5.1 – Up to 10% overloads or overloads not directly caused by wind

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name
1531	BALLYADA	3801	MIDLETON
1531	BALLYADA	5481	WHITEGAT
1642	CASHLA	5172	TYNAGH
1921	COW CROSS	4721	RAFFEEN
1921	COW CROSS	5481	WHITEGATE
2001	CULLENAG	5441	WATERFORD
2561	FINGLAS URBAN	3781	MCDERMOT
2741	GREAT ISLAND	3441	KILMURRY
3201	KNOCKRAHA	3801	MIDLETON
3261	KILKENNY	3341	KELLIS
4382	OLDSTREE	5172	TYNAGH

Table 5.1cont – Up to 10% overloads or overloads not directly caused by wind

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name
4721	RAFFEEN	5181	TRABEG
4721	RAFFEEN	5181	TRABEG
4941	SHANNON BRIDGE	22419	DALLOW TEE
4941	SHANNON BRIDGE	31019	IKERIN TEE
70510	BALLYLUMFORD	78511	EDEN 1A
70510	BALLYLUMFORD	78512	EDEN 1B
75510	COOLKEERAGH	84412	LISAGHMORE
1181	ARVA	4221	NAVAN
1181	ARVA	4961	SHANKILL
1641	CASHLA	50019	SOMERSET TEE
1861	CARRICK ON SHANNON	2521	FLAGFROD
4481	PORTLAOISE	22419	DALLOW TEE
77510	DUNGANNON	87510	OMAGH
2041	CORDUFF	3761	MACETOWN
1881	CHARLEVILLE	3281	KILLONAN
1661	CASTLEBAR	1821	CLOON
1661	CASTLEBAR	2281	DALTON
4021	MALLOW	1881	CHARLEVILLE

6 Network studies – Task 2

6.1. This section describes AC load flow calculations for all portfolios and for the following two operational regimes:

i. Winter peak – maximised wind generation.

ii. Summer maximum – maximised wind generation.

6.2. It should be pointed out that an additional Portfolio 6 scenario is considered only in Task 2 work. Thus, Portfolio 6A studied in Task 1 has 1 GW of offshore wind generation, which is added on the Working Group request, while Portfolio 6B is based purely on indicative levelised cost criteria that led to only 70 MW of offshore wind generation. The difference between these two is in the wind farm grid locations and their installed capacities. These locations are given in *Appendix A*.

6.3. It should be pointed out that initial points for Task 2 analysis are the reinforced networks from the Task 1 work. The initial point for Task 2 analysis in terms of Portfolio 6B is the reinforced Portfolio 5 network from the Task 1 work.

6.4. A significant amount of new renewable generation is connected to the network in all six portfolios. It is assumed that this new renewable generation operates at unity power factor and does not provide any reactive power support to the transmission network. It is recognised that renewable generation is, in fact, capable of providing reactive support. However, the assumption is based on the following facts:

i. Many wind farms might be connected to the distribution network and consequently not able to contribute significantly to the transmission network in terms of reactive power support.

ii. The proposed wind farm locations are far from load centres and the reactive power cannot be transferred over long distances.

6.5. One of the main challenges for the Irish power system will be voltage and reactive power control considering that a significant number of conventional units capable of providing reactive power and located electrically close to the load centres will be replaced by wind generation located electrically far from the load centres with limited capability to provide reactive power. Therefore, one of the main challenges for all future electricity scenarios with a significant renewable penetration will be to establish an adequate voltage-reactive power control strategy to ensure that the system is secure under all plausible conditions.

6.6. The initial work in Task 2 was focused on AC load flow calculations to ensure power flow convergence for all portfolios and all operational regimes bearing in mind the following system security requirements (intact system):

i. All 110 kV, 220 kV, 275 kV and 400 kV busbars must have their voltage magnitudes within specified limits.

ii. Any conventional unit must have its MVAr generation below its Q limits.

iii. Turlough Hill units provide no reactive power for the intact system. This requirement ensures that these units will not exceed their MVAr limits in the contingency analysis.

6.7. If any of the requirements discussed above could not be met the following changes/rules/actions were introduced:

i. Generator voltage set points were changed.

ii. Only if really necessary the target voltages of load tap changing transformers (LTC) were changed.

iii. Using voltage security analysis a list of the most promising locations for the placement of additional reactive power support is established. It should be pointed here that the placement of the additional reactive power support was not based on rigorous optimisation procedures, instead simple voltage stability nodal based indices were used to determine the most promising locations.

iv. It should be pointed out that the voltage security tool used for this work is capable of preventing various control oscillations (tap changers, generator shitting/backing off VAr limits).

v. Considering that economic dispatches were fully based on the Task 1 work it was found that some portfolios had a serious lack of conventional generation in certain areas. Even with additional reactive support some of these areas remained prone to voltage instability or had serious under-voltage problems for a single contingency, or could be highly sensitive to any voltage-reactive power changes in control settings. To make such areas more robust with respect to voltage stability the solution was run at least one conventional unit originally not committed in the Task 1 economic dispatch.

6.8. The following conclusions were drawn from these initial studies:

- Power flow calculations without additional reactive power support were not able to converge for all portfolio and operating regimes. For all portfolios and all operating regimes the majority of per unit nodal voltages were less than 0.5 even after only a few iterations. This demonstrates the severity of the problem and how far were the initial points (taken from Task 1) from the power flow feasibility boundary.

- Running the ASSESS optimal power flow capable of adding additional VArs where necessary to determine a solvable initial point was not successful. This caused a shift in Task 2 analysis toward voltage security and stability using in-house tools and expertise.

- To resolve power flow divergence several different techniques were applied. The most successful one was to add fictitious generating units close to load centres.

- These fictitious generators were then removed one by one, starting with the one that provided the least reactive power. A voltage security tool was run for every single removed unit to determine the best possible locations for the capacitors required to replace this fictitious unit. To determine these locations voltage stability indices were calculated for all transmission nodes and decisions on capacitor placements were made using these indices. These voltage security studies show that significant reactive power support would be required in Dublin, South East, South West and Northern Ireland to ensure power flow convergence and the requirements discussed in 6.5.

- The most promising locations identified by using the voltage security tool are: Louth, Tandragee, Cavan, Gorman, Carrickmines, Great Island, Cullenagh, Killonan, Maynooth, Irishtown, Inchicore, Poolbeg, New Rafeen, Castlereagh, and Ballylumford.

- The additional reactive power requirements for summer maximum and winter peak operational regimes for all portfolios are given in *Table 6.1* and *Table 6.2*, respectively.

- It can be seen that for the summer maximum operating regimes the additional reactive power requirements vary from 700 MVAR to 1200 MVAr. Portfolios 3,5, 6A and 6B require some conventional units not committed in the original Task 1 dispatches. Thus in Portfolio 3 the original Task 1 dispatch assumes no conventional units in South-West. This region requires at least one conventional unit to maintain voltages within the specified limits in this region. Having no units in the South-West region led to a significant number of power flow convergence problems when running contingency analysis. To provide additional reactive power support the Aghada generation site is used for this portfolio. Similarly to support voltages in Northern Ireland in Portfolio 5, 6A and 6B it is found that using the Coolkeeragh unit can significantly improve voltage profile in this region and ensure contingency analysis more robust from the power flow convergence point of view.

- It can be seen that for the winter peak operating regimes the additional reactive power requirements vary from 900 MVAR to over 2400 MVAr. Three portfolios (5, 6A and 6B) require running certain conventional units which were not originally committed in the Task 1. The Coolkeeragh unit was therefore used for Portfolio 5 and 6A, while both Dublin Bay and Coolkeeragh were used for Portfolio 6A.

- With additional capacitors and units suggested in the following table power flow convergence was ensured for each portfolio and each operational regime. The identified network constraints for the intact system are discussed in the following sections, while the results of contingency analysis are summarised in *Section 6.3.*

Table 6.1 – Summer Maximum – Additional Reactive Power Requirements

	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A	Portfolio 6B
Additional Reactive Power Support (Nominal MVAr)	700	1000	1000	1000	1000	1200	1200
Units required to run(see *Point v, paragraph 6.7*)	n.a.	n.a.	Aghada site	n.a.	Coolkeeragh site	Coolkeeragh site	Coolkeeragh site

Table 6.2 – Winter Maximum – Additional Reactive Power Requirements

	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6A	Portfolio 6B
Additional Reactive Power Support (Nominal MVAr)	900	1200	1300	1500	2400	2300	2400
Units required to run (*see Point v, paragraph 6.7*)	n.a.	n.a.	.n.a.	n.a.	Coolkeeragh site	Coolkeeragh Dublin Bay sites	Coolkeeragh site

6.1 Winter Maximum - Intact System

Portfolio 1 – Winter Maximum – Intact system

6.1.1. The following lines/transformers are overloaded for the intact system:

Table 6.3 - Winter Maximum - Intact System – Overloads--Portfolio 1

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
3282	KILLONAN		220/110 kV transformer	97.8	63.0
3282	KILLONAN		220 kV/110 transformer	97.0	63.0
3282	KILLONAN		220/110 kV transformer	163.1	120.0
2561	FINGLAS URBAN	3781	MCDERMOT	140.3	119.0
1741	CARRICKMINES	1801	COOKSTOWN	162.3	143.0
1742	CARRICKMINES		220/110 kV transformer	278.2	250.0
1742	CARRICKMINES		220/110 kV transformer	278.2	250.0
1741	CARRICKMINES	4511	POTTERY	129.7	119.0
2562	FINGLAS		220/110 kV transformer	270.3	250.0

Portfolio 2 – Winter Maximum – Intact system

6.1.2. The following lines/transformers are overloaded for the intact system:

Table 6.4 - Winter Maximum - Intact System – Overloads--Portfolio 2

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
3282	KILLONAN		220/110 kV transformer	173.4	120.0
2561	FINGLAS URBAN	3781	MCDERMOT	141.7	119.0
1741	CARRICKMINES	1801	COOKSTOWN	162.6	143.0
1742	CARRICKMINES	99990	220/110 kV transformer	275.1	250.0
1742	CARRICKMINES	99989	220/110 kV transformer	275.1	250.0
1741	CARRICKMINES	4511	POTTERY	129.8	119.0

Portfolio 3 – Winter Maximum - Intact system

6.1.3. The following lines/transformers are overloaded for the intact system:

Table 6.5 - Winter Maximum - Intact System – Overloads—Portfolio 3

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
3282	KILLONAN		220/110 kV transformer	178.0	120.0
2561	FINGLAS URBAN	3781	MCDERMOT	139.0	119.0
1741	CARRICKMINES	1801	COOKSTOWN	162.3	143.0
1741	CARRICKMINES	4511	POTTERY	129.7	119.0
1742	CARRICKMINES		220/110 kV transformer	270.4	250.0
1742	CARRICKMINES		220/110 kV transformer	270.4	250.0
4941	SHANNONBRIDGE	22419	DALLOW TEE	105.6	103.0
2562	FINGLAS		220/110 kV transformer	255.1	250.0

Portfolio 4- Winter Maximum - Intact system

6.1.4. The following lines/transformers are overloaded for the intact system:

Table 6.6 - Winter Maximum - Intact System – Overloads—Portfolio 4

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
3282	KILLONAN		220/110 kV transformer	176.0	120.0
2561	FINGLAS URBAN	3781	MCDERMOT	137.4	119.0
2562	FINGLAS		220/110 kV transformer	288.6	250.0
1741	CARRICKMINES	4511	POTTERY	130.7	119.0
4941	SHANNONBRIDGE	22419	DALLOW TEE	113.6	103.0
1741	CARRICKMINES	1801	COOKSTOWN	150.0	143.0

Portfolio 5- Winter Maximum - Intact system

6.1.5. The following lines/transformers are overloaded for the intact system:

Table 6.7 - Winter Maximum - Intact System – Overloads- Portfolio 5

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
1042	AGHADA		220/110 kV transformer	202.8	125.0
3852	MAYNOOTH		220/110 kV transformer	200.2	125.0
2562	FINGLAS		220/110 kV transformer	312.0	250.0
4941	SHANNONBRIDGE	22419	DALLOW TEE	126.4	103.0
2561	FINGLAS URBAN	3781	MCDERMOT	140.5	119.0
1741	CARRICKMINES	4511	POTTERY	130.1	119.0
2041	CORDUFF	3761	MACETOWN	151.1	143.0
4481	PORTLAOISE	22419	DALLOW TEE	104.6	103.0
1741	CARRICKMINES	1801	COOKSTOWN	143.2	143.0

Portfolio 6A- Winter Maximum – Intact system

6.1.6. The following lines/transformers are overloaded for the intact system:

Table 6.8 - Winter Maximum - Intact System – Overloads- Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
1122	ARKLOW		220/110 kV transformer	110.0	63.0
1121	ARKLOW	4911	SHELTON	153.7	103.0
3282	KILLONAN		220/110 kV transformer	83.9	63.0
3282	KILLONAN		220/110 kV transformer	83.2	63.0
1741	CARRICKMINES	4511	POTTERY	151.8	119.0
1741	CARRICKMINES	1801	COOKSTOWN	171.7	143.0
3282	KILLONAN		220/110 kV transformer	140.0	120.0
2561	FINGLAS URBAN	3781	MCDERMOT	135.5	119.0
2041	CORDUFF	3761	MACETOWN	160.4	143.0
3082	INCHICORE	3122	IRISHTOWN	635.8	593.0
1122	ARKLOW		220/110 kV transformer	132.7	125.0
2562	FINGLAS		220/110 kV transformer	262.0	250.0
4941	SHANNONBRIDGE	22419	DALLOW TEE	107.6	103.0
5141	TARBERT	5261	TRIEN	170.9	168.0
4991	SORNE HILL	5361	TRILLICK	127.6	126.0

Portfolio 6B – Winter Maximum – Intact system

6.1.7. The following lines/transformers are overloaded for the intact system:

Table 6.9 - Winter Maximum - Intact System – Overloads- Portfolio 6B

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
2562	FINGLAS		220/110 kV transformer	376.3	250.0
2041	CORDUFF	3761	MACETOWN	191.6	143.0
2571	FINGLAS RURAL	3761	MACETOWN	170.3	128.0
1281	BALLYLICKEY	2221	DUNMANWAY	163.8	126.0
3282	KILLONAN		220/110 kV transformer	81.9	63.0
1931	CUNGHILL	4981	SLIGO	163.1	126.0
3282	KILLONAN		220/110 kV transformer	81.2	63.0
4941	SHANNONB	22419	DALLOW TEE	132.2	103.0
2561	FINGLAS URBAN	3781	MCDERMOT	143.8	119.0
2842	GORMAN	99976	220/110 kV transformer	293.1	250.0
3282	KILLONAN	99967	220/110 kV transformer	136.7	120.0
4481	PORTLAOI	22419	DALLOW TEE	110.3	103.0
1741	CARRICKMINES	4511	POTTERY	129.3	119.0
3501	LANESBORO	4001	MULLINGAR	134.5	126.0
1361	BALLYDINE	2001	CULLENAGH	130.7	126.0
5464	WOODLAND	99935	400/220 kV transformer	513.5	500.0
1741	CARRICKMINES	1801	COOKSTOWN	146.9	143.0

6.2 Summer Maximum - Intact System

Portfolio 1 – Summer Maximum -Intact System

6.2.1. The following lines/transformers are overloaded for the intact system:

Table 6.10 - Summer Maximum – Intact System – Overloads-Portfolio 1

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
3282	KILLONAN		220/110 kV transformer	75.1	63.0
3282	KILLONAN		220/110 kV transformer	125.2	120.0

Portfolio 2 – Summer Maximum -Intact System

6.2.2. The following lines/transformers are overloaded for the intact system:

Table 6.11 - Summer Maximum – Intact System – Overloads-Portfolio 2

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
3282	KILLONAN		220/110 kV transformer	79.8	63.0
1881	CHARLEVILLE	2881	GLENLARA	117.4	107.0
4941	SHANNONBRIDGE	22419	DALLOW TEE	81.4	72.0
3282	KILLONAN		220/110 kV transformer	133.0	120.0
1881	CHARLEVILLE	3281	KILLONAN	77.6	77.0

Portfolio 3 – Summer Maximum -Intact System

6.2.3. The following lines/transformers are overloaded for the intact system:

Table 6.12 – Summer Maximum – Intact System – Overloads-Portfolio 3

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
3282	KILLONAN		220/110 kV transformer	74.9	63.0
3282	KILLONAN		220/110 kV transformer	74.3	63.0
4941	SHANNONBRIDGE	22419	DALLOW TEE	83.1	72.0
1881	CHARLEVILLE	2881	GLENLARA	117.6	107.0
3282	KILLONAN		220/110 kV transformer	127.3	120.0
4481	PORTLAOISE	22419	DALLOW TEE	72.0	72.0
2041	CORDUFF	3761	MACETOWN	111.3	111.0

Portfolio 4 – Summer Maximum -Intact System

6.2.4. The following lines transformers are overloaded for the intact system:

Table 6.13 - Summer Maximum - Intact System – Overloads-Portfolio 4

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
4941	SHANNONBRIDGE	22419	DALLOW TEE	82.8	72.0
1881	CHARLEVILLE	2881	GLENLARA	117.5	107.0
3282	KILLONAN		220/110 kV transformer	70.6	63.0
3282	KILLONAN		220/110 kV transformer	70.0	63.0
1881	CHARLEVILLE	3281	KILLONAN	76.9	72.0
4481	PORTLAOISE	22419	DALLOW TEE	71.2	72.0

Portfolio 5 – Summer Maximum –Intact System

6.2.5. The following lines/transformers are overloaded for the intact system:

Table 6.14 - Summer Maximum - Intact System – Overloads-Portfolio 5

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
3282	KILLONAN		220/110 kV transformer	159.6	120.0
4941	SHANNONBRIDGE	22419	DALLOW TEE	89.6	72.0
4481	PORTLAOISE	22419	DALLOW TEE	77.2	72.0
2041	CORDUFF	3761	MACETOWN	114.0	111.0

Portfolio 6A – Summer Maximum –Intact System

6.2.6. The following lines/transformers are overloaded for the intact system:

Table 6.15 - Summer Maximum - Intact System – Overloads-Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Bus1 ID	Bus1 Name
3282	KILLONAN		220/110 kV transformer	165.8	120.0
2041	CORDUFF	3761	MACETOWN	125.1	111.0
1041	AGHADA	5481	WHITEGATE	119.1	107.0
4941	SHANNONB	22419	DALLOW TEE	79.4	72.0
1042	AGHADA		220/110 kV transformer	135.5	125.0

Portfolio 6B– Summer Maximum –Intact System

6.2.7. The following lines/transformers are overloaded for the intact system:

Table 6.16 - Summer Maximum - Intact System – Overloads-Portfolio 6B

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	MVA	Rating MVA
2041	CORDUFF	3761	MACETOWN	162.6	111.0
2571	FINGLAS RURAL	3761	MACETOWN	160.4	120.0
3282	KILLONAN		220/110 kV transformer	80.1	63.0
3282	KILLONAN		220/110 kV transformer	79.4	63.0
4941	SHANNONBRIDGE	22419	DALLOW TEE	80.8	72.0
3282	KILLONAN		220/110 kV transformer	133.7	120.0

6.3 CONTINGENCY STUDIES

6.3.1 Summer Maximum – Network Contingency Studies

Summer Maximum – Power Flow Non-Convergence Cases Caused by a Single Contingency

6.3.1.1. For the summer maximum operating regime all single contingencies that cause power flow non-convergence were identified. These contingencies were analysed in more depth and for many of them it was observed that:

- a significant number of LTC transformers move their tap positions,
- many generators hit or back off their VAr limits,
- voltage security tool identifies a number of control oscillations.

Where possible, simple solutions can be found to ensure power flow convergence, however for many of them in depth voltage stability studies are required to identify the problem cause and measures to deal with it.

Table 6.17 –Summer Maximum -Single Contingencies Causing Power Flow Non-Convergence

Sum_ID	Contingency
1	3261 KILKENNY- 3341 KELLIS
2	2741 GREAT ISLAND – 3441 KILMURRY
3	4941 SHANNONBRIDGE – 31019 IKERIN Tee
4	2941 HAROLDS – 4651 RINGSEND
5	2562 FINGLAS-2962 HUNTSTOWN
6	2962 HUNTSTOWN 220/110 kV TRANSFORMER

6.3.1.2. The 110 kV network section originating from the Great Island substation going via the Kilmurry 110 kV substation and the Kilkenny 110 kV substation toward the Athy 110 kV substation is one of the most vulnerable network section in terms of voltage-reactive power issues. The 110 kV lines Kilkenny to Kellis and Great Island to Kilmurry are the main reactive power feeders for the 110 kV load connected to Kilkenny and Kilmurry. If any of these lines is out of service a local voltage collapse and/or serious voltage degradation across the network section will occur. This network section is highly voltage sensitive and further in depth voltage stability studies are required to make decision on the best voltage-reactive power control strategy to be applied.

6.3.1.3. An outage of the 110 kV line between Shannonbridge and Ikerin Tee causes a local voltage instability in the area that includes the following 110 kV substations: Ikerin Tee, Thurles, Lisheen and Cahir. This area already has capacitors installed at Cahir and Thurles and the identified problem is certainly not caused by renewable generation.

6.3.1.4. An outage of the 110 kV line between Harolds and Ringsend means a lack of reactive power support to Harolds. Further investigation showed that a 60 MVAr capacitor would resolve this non-convergent issue.

6.3.1.5. The contingencies whose identifier (*Sum_ID* the first column in *Table 6.17*) are *Sum_ID*=5 and *Sum_ID*=6 are related to the loss of reactive power support coming from the Huntstown unit, which is for many portfolios the only conventional unit considered in the Dublin region, especially for the summer maximum operational regime. Considering that the conventional units in the Dublin region in all portfolios usually run close to their upper VAr limits, any contingency related to these units makes a significant impact on the local voltage profile, reactive power flows and tap changers.

Portfolio 1 – Summer Maximum – N-1 Contingency analysis

6.3.1.6. It is found that all 110 kV, 220 kV, 275 kV and 400 kV busbar voltages remain within the limits 0.9 – 1.1 p.u. for any single contingency.

6.3.1.7. Several 220/110 kV (or 275/110 kV) transformers can be overloaded due to a single contingency. The transformers at Inchicore, Finglas, Carrickmines, Kellis, Woodland, Knockraha, Castlereagh and Poolbeg, and Arklow are found overloaded (mostly when the other parallel transformer is out of service).

6.3.1.8. The following lines are overloaded due to a single contingency:

Table 6.18 - Summer Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 1[14]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
4941	SHANNON BRIDGE	31019	IKERIN TEE	1	135.51	93
3261	KILKENNY	3341	KELLIS	1	131.96	107
4382	OLDSTREET	5172	TYNAGH	1	131.59	431
3082	INCHICORE	3122	IRISHTOWN	1	131.18	593
1742	CARRICKMINES	3122	IRISHTOWN	1	130.94	593
2561	FINGLAS URBAN	3781	MCDERMOT	4	126.02	119
3201	KNOCKRAHA	3221	KILBARRY	1	124.77	107
3201	KNOCKRAHA	3221	KILBARRY	1	119.96	107
4522	PROSPECT	5142	TARBERT	3	119.79	381
1642	CASHLA	5172	TYNAGH	4	141.08	431
2041	CORDUFF	3761	MACETOWN	2	153.89	111

Portfolio 2 – Summer Maximum – N-1 Contingency analysis

6.3.1.9. A small number of single contingencies can cause overvoltages in this portfolio, especially in Co. Mayo and Co. Sligo. An addition of one 50 MVAr (nominal) reactor at both Bellacorick and Moy can successfully eliminate these overvoltages.

6.3.1.10. Undervoltages were not identified for any single contingency.

6.3.1.11. Several 220/110 (or 275/110 kV) transformers can be overloaded due to a single contingency. The transformers at Inchicore, Finglas, Carrickmines, and Castlereagh(275/110kV) are found overloaded (mostly when the other parallel transformer is out of service).

6.3.1.12. The following lines are overloaded due to a single contingency:

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[14] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.10* –Portfolio 1.

Table 6.19 - Summer Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 2[15]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
2041	CORDUFF	3761	MACETOWN	4	176.11	111
1881	CHARLEVILLE	4021	MALLOW	1	153.43	72
5141	TARBERT	5261	TRIEN	1	153.64	120
2561	FINGLAS URBAN	3781	MCDERMOT	4	127.44	119
4481	PORTLAOISE	22419	DALLOW TEE	8	121.31	72
3281	KILLONAN	3541	LIMERICK	1	120.05	86
3281	KILLONAN	3541	LIMERICK	1	120.05	86
2571	FINGLAS RURAL	3761	MACETOWN	1	118.61	120

Portfolio 3 – Summer Maximum – N-1 Contingency analysis

6.3.1.13. Similarly as in portfolio 2, a small number of single contingencies can cause overvoltages especially in Co. Mayo and Sligo. An addition of one 50 MVAr (nominal) reactor at both Bellacorick and Moy eliminate these overvoltages.

6.3.1.14. Undervoltages were not identified for any single contingency.

6.3.1.15. Several 220/110 kV/kV transformers can be overloaded due to a single contingency. The transformers at Inchicore, Finglas, Carrickmines, Castlereagh (275/110 kV), and Woodland are found overloaded when the parallel transformer is out of service.

6.3.1.16. The following lines are overloaded due to a single contingency:

Table 6.20 - Summer Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 3[15]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
2041	CORDUFF	3761	MACETOWN	6	188.70	111
3221	KILBARRY	4021	MALLOW	4	156.61	72
1881	CHARLEVILLE	3281	KILLONAN	2	153.87	72
1881	CHARLEVILLE	4021	MALLOW	5	153.77	72
5141	TARBERT	5261	TRIEN	1	153.64	120
4382	OLDSTREET	5172	TYNAGH	1	131.53	431
2571	FINGLAS RURAL	3761	MACETOWN	1	129.96	120

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[15] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.11* –Portfolio 2, *Table 6.12* – Portfolio 3.

Table 6.20cont - Summer Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 3

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
1642	CASHLA	5172	TYNAGH	3	129.96	431
1931	CUNGHILL	4981	SLIGO	2	126.56	107
4481	PORTLAOISE	22419	DALLOW TEE	15	124.93	72
2561	FINGLAS URBAN	3781	MCDERMOT	4	123.86	119
1401	BELLACORICK	1661	CASTLEBA	1	116.86	107
3881	MACROOM	5181	TRABEG	1	115.44	
3281	KILLONAN	3541	LIMERICK	2	115.4	86
3281	KILLONAN	3541	LIMERICK	1	115.24	86
2202	DUNSTOWN	5202	TURLOUGH HILL	1	115.05	351

Portfolio 4 – Summer Maximum - N-1 Contingency analysis

6.3.1.17. Overvoltages discussed above for Portfolio 3 remain in Portfolio 4.

6.3.1.18. Undervoltages were not identified for any single contingency.

6.3.1.19. Several 220/110 kV/kV transformers are overloaded due to a single contingency. The transformers at Inchicore, Finglas, Carrickmines, Castlereagh(275/110 kV) are found overloaded (mostly when the other parallel transformer is out of service).

6.3.1.20. The following lines are overloaded due to a single contingency:

Table 6.21 - Summer Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 4[16]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
2041	CORDUFF	3761	MACETOWN	2	172.00	143
3221	KILBARRY	4021	MALLOW	1	156.06	103
1881	CHARLEVILLE	3281	KILLONAN	21	155.13	103
1881	CHARLEVILLE	4021	MALLOW	1	153.77	103
5141	TARBERT	5261	TRIEN	2	136.68	128
2561	FINGLAS URBAN	3781	MCDERMOT	5	133.11	119
4481	PORTLAOISE	22419	DALLOW TEE	12	124.93	103
3281	KILLONAN	3541	LIMERICK	1	123.12	126
3281	KILLONAN	3541	LIMERICK	2	119.58	126

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[16] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.13* – Portfolio 4.

Portfolio 5 – Summer Maximum – N-1 Contingency analysis

6.3.1.21. Several 220/110 kV/kV transformers can be overloaded due to a single contingency. The transformers at Inchicore, Finglas, Castlereagh(275/110 kV) and Poolbeg are found overloaded (mostly when the other parallel transformer is out of service).

6.3.1.22. Undervoltages were not identified for any single contingency.

6.3.1.23. A small number of single contingencies that will cause overvoltages is identified, especially in Northern Ireland and South-West. These overvoltages can be successfully eliminated by the addition of small reactors.

6.3.1.24. The following lines are overloaded due to a single contingency:

Table 6.22 -Summer Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 5[17]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
2041	CORDUFF	3761	MACETOWN	8	174.43	111
2002	CULLENAGH	2742	GREAT ISLAND	1	149.64	229
4481	PORTLAOISE	22419	DALLOW TEE	86	137.00	72
1881	CHARLEVILLE	3281	KILLONAN	2	134.27	72
79010	ENNISKILEN	87510	OMAGH	1	123.79	82
79010	ENNISKILEN	87510	OMAGH	1	123.79	82
2561	FINGLAS URBAN	3781	MCDERMOT	4	121.55	119
1881	CHARLEVILLE	2881	GLENLARA	1	118.94	107
2571	FINGLAS RURAL	3761	MACETOWN	1	117.52	120
2741	GREAT ISLAND	3441	KILMURRY	1	117.50	107

Portfolio 6A – Summer Maximum – N-1 Contingency analysis

6.3.1.25. Several 220/110 kV/kV transformers can be overloaded due to a single contingency. The transformers at Inchicore, Finglas, Castlereagh(275/110 kV), Trillick and Letterkenny are found overloaded mostly when the other parallel transformer is out of service.

6.3.1.26. A small number of single contingencies that will cause overvoltages is identified, especially in Northern Ireland and South-West. These overvoltages can be successfully eliminated by the addition of small reactors.

6.3.1.27. Undervoltages were not identified for any single contingency.

6.3.1.28. The following lines are overloaded due to a single contingency:

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[17] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.14* – Portfolio 5.

Table 6.23 - Summer Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 6A[18]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
4361	OUGHTRAGH	43619	OUGHTRAGH TEE	3	176.68	107
3581	LETTERKENNY	5361	TRILLICK	2	150.73	107
2202	DUNSTOWN	5202	TURLOUGH	4	146.66	351
3842	MAYNOOTH	5202	TURLOUGH	2	145.47	351
2741	GREAT ISLAND	3441	KILMURRY	1	138.85	107
1861	CARRICK ON SHANNON	2521	FLAGFORD	1	135.17	107
1861	CARRICK ON SHANNON	2521	FLAGFORD	1	134.96	107
2521	FLAGFORD	4981	SLIGO	1	133.11	107
2561	FINGLAS URBAN	3781	MCDERMOT	4	125.69	119
2521	FLAGFORD	4981	SLIGO	1	125.13	107
1651	CLAHANE	5281	TRALEE	1	124.01	107
1181	ARVA	1861	CARRICK ON SHANNON	2	118.35	107
2042	CORDUFF	2562	FINGLAS	1	117.47	431
2042	CORDUFF	2562	FINGLAS	1	117.47	431
1281	BALLYLICKEY	2221	DUNMANWAY	2	116.67	107

Portfolio 6B – Summer Maximum – N-1 Contingency analysis

6.3.1.29. A number of single contingencies cause overvoltages especially in Northern Ireland and Co. Mayo and Co. Sligo. The contingency studies are repeated with additional small reactors and it is found that these overvoltages can be successfully eliminated.

6.3.1.30. Several 220/110 kV/kV transformers can be overloaded due to a single contingency. The transformers at Woodland, Finglas, Castlereagh (275/110 kV), Arklow, Trillick and Letterkenny are found overloaded.

6.3.1.31. Undervoltages were not identified for any single contingency.

6.3.1.32. The following lines are overloaded due to a single contingency:

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[18] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.15* – Portfolio 6A

Table 6.24 - Summer Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 6B[19]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
4361	OUGHTRAG	43619	OUGHTRAGH TEE	3	176.67	107
3581	LETTERKENNY	5361	TRILLICK	2	150.73	107
3261	KILKENNY	3341	KELLIS	1	146.13	107
2202	DUNSTOWN	5202	TURLOUGH HILL	2	142.79	351
3842	MAYNOOTH	5202	TURLOUGH HILL	1	139.87	351
1861	CARRICK ON SHANNON	2521	FLAGFORD	1	137.07	107
1861	CARRICK ON SHANNON	2521	FLAGFORD	1	136.86	107
2521	FLAGFORD	4981	SLIGO	1	133.12	107
2042	CORDUFF	2562	FINGLAS	1	130.78	431
2042	CORDUFF	2562	FINGLAS	1	130.78	431
2561	FINGLAS URBAN	3781	MCDERMOT	4	126.01	119
2521	FLAGFORD	4981	SLIGO	1	125.15	107
1651	CLAHANE	5281	TRALEE	1	124.01	107
1181	ARVA	1861	CARRICK ON SHANNON	1	118.12	107
3281	KILLONAN	3541	LIMERICK	2	118.08	86
4481	PORTLAOISE	22419	DALLOW TEE	6	116.92	72
1281	BALLYLICKEY	2221	DUNMANWAY	2	116.70	107
3082	INCHICORE	4472	POOLBEG	1	116.66	351
3281	KILLONAN	3541	LIMERICK	1	116.62	86

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[19] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.16*– Portfolio 6B.

6.3.2 Winter Maximum – Contingency Studies

Winter Maximum – Power Flow Non-Convergence Cases Caused by a Single Contingency

6.3.2.1. Similarly as in *6.3.1* the power flow non-divergence cases caused by a single contingency are discussed first.

Table 6.25 - Winter Maximum – Single Contingencies Causing Power Flow Non-Convergence

Win_ID	Contingency
1	3261 KILKENNY- 3341 KELLIS
2	2741 GREATIS- 3441 KILMURRY
3	4941 SHANNONBRIDGE -31019 IKERIN TEE
4	2941 HAROLDS- 4651 RINGSEND
5	1742 CARRICKMINES – 220/110 kV TRANSFORMER
6	1642 CASHLA- 5172 TYNAGH
7	3081 INCHICORE- 3871 MILLTOWN
8	3261 KILKENNY- 3441 KILMURRY
12	2562 FINGLAS-220/110 kV TRANSFORMER
13	2962 HUNTSTOWN 220/110 kV TRANSFORMER
14	2042 CORDUFF- 2972 HUNTSTOWN
15	2562 FINGLAS- 2962 HUNTSTOWN
16	5142 TARBERT-220/110 kV TRANSFORMER
18	1742 CARRICKMINES- 3122 IRISHTOWN
19	3944 MONEYPOINT- 5494 WEST MIDLAND 400kV
20	4384 OLDSTREET- 5464 WOODLAND
21	5462 WOODLAND –220/110 kV TRANSFORMER

6.3.2.2. The contingencies whose identifiers (*Win_ID* the first column in the table above) are 1, 2, 3, and 4 have been already discussed for the summer maximum scenario (see *6.3.1*).

6.3.2.3. A single outage of the 220 kV transformers connected to Carrickmines (*Win_ID* =5) causes a local voltage collapse considering that a significant number of 110 kV busbars connected to the 110 kV Carrickmines busbar have quite low post-contingency voltages (about 0.84 to 0.9). A new 220/110 transformer at Carrickmines would be required to achieve power flow convergence in this particular situation.

6.3.2.4. An outage of the 220 kV line between Cashla and Tynagh (*Win_ID*=5) is a control oscillation problem, which can be successfully solved using 'mechanisms' that can prevent such oscillations in the power flow algorithm.

6.3.2.5. An outage of the 110 kV line Inchicore to Milltown causes low voltages at Milltown and the 33 kV network connected to this busbar.

6.3.2.6. An outage of the 110 kV line Kilkenny to Kilmurry causes the same network problems as the contingencies Wind_Id=1 and Wind_Id=2.

6.3.2.7. It can be seen that single outages of the main corridors and transformers connected to Tynagh, Moneypoint, Huntstown, Woodland and Dublin Bay will cause power flow divergence. Considering a lack of generation in the Dublin region a loss of any of these units or the corresponding corridors/transformers connected to these units causes serious voltage degradation and excessive reactive power flows in this region. This issue deserves special attention considering that reactive power cannot be transmitted over long distances and replacing the Dublin generation in terms of reactive power will be a challenging task for all portfolios with high renewable penetration. The next important point here is that connecting the new conventional generation at Moneypoint, Aghada and even Poolbeg might require certain network reinforcements that are not considered in this work.

Portfolio 1 – Winter Maximum – N-1 Contingency analysis

6.3.2.8. Due to single contingency, transformers at Inchicore, Kellis, Finglas, Maynooth, Woodland and Castlereagh are loaded more than 110%. Special attention should be paid to the transformers located in the Dublin area considering that their loading due to a single contingency can be significantly higher than 110%.

6.3.2.9. Several single contingencies can cause undervoltages especially:

- across the 110 kV network section: Thurles, Lisheen, Cahir. The reactive power support for both 110 kV substation Thurles and Lisheen is dependent on the MVAr flows infeed from the 110 kV Cahir substation. It is found that a new capacitor whose nominal MVAr rating is 20MVAr would guarantee that the voltage magnitudes across this network section are larger than the planning threshold of 0.9 p.u. for any single contingency;

- in Northern Ireland it is observed that several 110 kV substations run split (for example Newry, Rathgael and Ballynahinch) and these stations are often radially connected to a central 110 kV substation (for example Tandragee or Castlereagh). They can be prone to a serious voltage drop when the line connecting the substation with the central station is out of service. Thus, for example the 110 kV Newry substation runs split with two 110 kV busbar section radially connected to the 110 kV substation Tandragee via two parallel 110 kV lines. A single outage of any of these two lines causes a significant voltage drop at the corresponding busbar section where the line that is out of service is connected. Similarly, several other 110 kV sections are prone to the same problem (Rathgael, Ballynahinch);

- a single outage of the 110 kV line between Kilteel and Maynooth will cause a significant voltage drop at the 110 kV busbars Kilteel and Monread . With a new capacitor whose MVAr rating is 20MVAr connected to Kilteel the voltage magnitudes at these two busbars would remain above the planning threshold of 0.9 p.u. for any single contingency.

6.3.2.10. The following lines are overloaded due to a single contingency:

Table 6.26 - Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 1[20]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
2041	CORDUFF	3761	MACETOWN	2	180.92	143
4472	POOLBEG	17431	CARICKMINES_PST	1	174.37	267
2202	DUNSTOWN	5202	TURLOUGH	3	159.15	351
2571	FINGLAS RURAL	3761	MACETOWN	2	156.15	128
3082	INCHICORE	3122	IRISHTOWN	1	133.14	593
1742	CARRICKMINES	3122	IRISHTOWN	1	132.67	593
1201	ARTANE	2561	FINGLAS URBAN	1	131.63	120

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[20] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.3*– Portfolio 1.

Table 6.26cont - Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 1

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
86511	NEWRY 1A	90011	TANDRAGEE	1	128.82	103
86512	NEWRY 1B	90011	TANDRAGEE	1	128.82	103
3521	LOUTH	4061	MULLAGHARLIN	1	124.31	126
2101	DUNDALK	3521	LOUTH	2	121.18	126
76512	DONEGALL(BELFAST)	91012	PSW	3	120.32	82
1741	CARRICKMINESS	2481	FASSAROE EAST	1	115.60	126

Portfolio 2 – Winter Maximum – N-1 Contingency analysis

6.3.2.11. Several single contingencies already noticed in Portfolio 1 cause undervoltages, especially:

- an outage of the 220/110 kV Carrickmines transformer will cause undervoltages at: Cookstown, Fassaroe East and Fassoroe West;
- an outage of the 220/110 kV Finglas transformer will cause undervoltages at: Finglas Urban, Cabra, McDermott, Artane, Wolfetown;
- the undervoltages in Northern Ireland discussed for Portfolio 1 above remain in Portfolio 2, as well.

6.3.2.12. A small number of single contingencies can cause overvoltages especially in Co. Mayo and Sligo. An addition of one 30 MVAr (nominal) reactor at Bellacorick eliminates these overvoltages.

6.3.2.13. Due to a single contingency transformers at: Inchicore, Carrickmines, Kellis, Finglas, Maynooth, Woodland, Huntstown and Castlereagh are loaded more than 110%.

6.3.2.14. The following lines are overloaded due to a single contingency:

Table 6.27 - Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 2[21]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
2041	CORDUFF	3761	MACETOWN	2	165.92	143
5141	TARBERT	5261	TRIEN	3	149.73	128
2571	FINGLAS RURAL	3761	MACETOWN	2	140.71	128
1201	ARTANE	2561	FINGLAS URBAN	1	133.16	120
86511	NEWRY 1A	90011	TANDRAGEE 1A	1	129.61	103
86512	NEWRY 1B	90011	TANDRAGEE 1A	1	129.61	103
3261	KILKENNY	3341	KELLIS	1	129.35	126
3521	LOUTH	4061	MULLAGHA	1	123.62	126

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[21] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.4*– Portfolio 2.

Table 6.cont - Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 2

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
1741	CARRICKMINES	2491	FASSAROE WEST	1	121.46	126
2101	DUNDALK	3521	LOUTH	2	120.61	126
76512	DONEGALL (BELFAST)	91012	WEST1B	3	119.18	82
4941	SHANNONBRIDGE	22419	DALLOW TEE	7	116.84	103

Portfolio 3 – Winter Maximum – N-1 Contingency analysis

6.3.2.15. Undervoltages discussed above for Portfolio 2 remain in Portfolio 3.

6.3.2.16. Overvoltages discussed above for Portfolio 2 remain in Portfolio 3.

6.3.2.17. Due to a single contingency transformers at Inchicore, Kellis, Carrickmines, Finglas, Maynooth, Woodland, Huntstown and Castlereagh,are loaded more than 110%.

6.3.2.18. The following lines are overloaded due to a single contingency:

Table 6.28 - Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 3[22]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
2041	CORDUFF	3761	MACETOWN	4	183.14	143
2571	FINGLAS RURAL	3761	MACETOWN	2	158.82	128
5141	TARBERT	5261	TRIEN	3	149.78	128
3261	KILKENNY	3341	KELLIS	1	131.71	126
3082	INCHICORE	3122	IRISHTOWN	1	131.28	593
1742	CARRICKMINES	3122	IRISHTOWN	1	130.34	593
1201	ARTANE	2561	FINGLAS URBAN	1	130.27	120
86511	NEWRY1A	90011	TANDRAGEE1A	1	129.25	103
86512	NEWRY1B	90011	TANDRAGEE1A	1	129.25	103
3521	LOUTH	4061	MULLAGHARLIN	1	123.90	126
4941	SHANNONBRIDGE	22419	DALLOW TEE	13	122.13	103
3082	INCHICORE	4472	POOLBEG	1	120.87	267
2101	DUNDALK	3521	LOUTH	2	120.82	126
1741	CARRICKM	2481	FASSAROE EAST	1	120.46	143
76512	DONEGALL (BELFAST)	91012	PSW1B	3	117.32	82
1741	CARRICKMINES	2491	FASSAROE WEST	1	116.99	126
2202	DUNSTOWN	5202	TURLOUGH HILL	1	116.56	351

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[22] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.5* –Portfolio 3.

Portfolio 4– Winter Maximum – N-1 Contingency analysis

6.3.2.19. Undervoltages discussed above for Portfolio 2 remain in Portfolio 4.

6.3.2.20. Overvoltages discussed above for Portfolio 2 remain in Portfolio 4.

6.3.2.21. Due to a single contingency transformers at Finglas, Inchicore, Kellis, Carrickmines, Maynooth, Woodland, and Castlereagh,are loaded more than 110%. Special attention should be paid to the transformers located in the Dublin area considering that their loading due to a single contingency can be significantly higher than 110%.

6.3.2.22. The following lines are overloaded due to a single contingency:

Table 6.29 - Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 4[23]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
2041	CORDUFF	3761	MACETOWN	2	174.93	143
2571	FINGLAS RURAL	3761	MACETOWN	2	150.15	128
5141	TARBERT	5261	TRIEN	2	148.56	128
1201	ARTANE	2561	FINGLAS URBAN	1	133.18	120
86512	NEWRY 1B	90011	TANDRAGEE 1A	1	130.05	103
86511	NEWRY 1A	90011	TANDRAGEE 1A	1	130.05	103
4941	SHANNONBRIDGE	22419	DALLOW TEE	43	129.72	103
3261	KILKENNY	3341	KELLIS	1	128.32	126
76512	DONEGALL (BEFAST)	91012	PSW	3	126.07	82
3521	LOUTH	4061	MULLAGHARLIN	1	124.06	126
2202	DUNSTOWN	5202	TURLOUGH	6	122.93	351
2101	DUNDALK	3521	LOUTH	2	120.96	126
1741	CARRICKMINES	2491	FASSAROE WEST	1	119.67	126

Portfolio 5– Winter Maximum – N-1 Contingency analysis

6.3.2.23. Undervoltages discussed above for Portfolio 2 remain in Portfolio 5.

6.3.2.24. A small number of single contingencies cause overvoltages especially in Co. Limerick, Dublin area and Northern Ireland. An addition of one 30 MVAr (nominal) reactor in these regions can eliminate these overvoltages.

6.3.2.25. Due to a single contingency transformers at Finglas, Inchicore, Huntstown, Woodland, Letterkenny and Castlereagh, are loaded more than 110%.

6.3.2.26. The following lines are overloaded due to a single contingency:

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[23] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.6*–Portfolio 4.

Table 6.30 – Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 5[24]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
86512	NEWRY 1B	90011	TANDRAGEE 1A	1	139.33	103
86511	NEWRY 1A	90011	TANDRAGEE 1A	1	139.33	103
1881	CHARLEVILLE	2881	GLENLARA	1	135.43	126
1201	ARTANE	2561	FINGLAS URBAN	1	132.10	120
79010	ENNISKILEN	87510	OMAGH	1	130.09	103
79010	ENNISKILEN	87510	OMAGH	1	130.09	103
3581	LETTERKENNY	5361	TRILLICK	1	120.02	126
2202	DUNSTOWN	5202	TURLOUGH HILL	3	118.42	351
3842	MAYNOOTH	5202	TURLOUGH HILL	1	117.88	351
3521	LOUTH	4061	MULLAGHARLIN	1	116.06	126

Portfolio 6A- Winter Maximum – N-1 Contingency analysis

6.3.2.27. Undervoltages discussed above for Portfolio 2 remain in Portfolio 5.

6.3.2.28. A small number of single contingencies cause small overvoltages especially in South-West (especially Ballilickey), at Shelton and Arklow, in Co. Mayo and Co. Sligo. An addition of one 30 MVAr (nominal) reactor in these regions can eliminate these overvoltages.

6.3.2.29. Due to a single contingency transformers at Finglas, Maynooth, Inchicore, Huntstown, Woodland, Letterkenny, Great Island, Shannonbridge, Trillick, Arklow and Castlereagh, are loaded more than 110%.

6.3.2.30. A small number of single contingencies that cause overvoltages is identified, especially in Co. Mayo and Sligo, at Ballilickey, at Shelton. With an addition of one 30 MVAr nominal reactors (one in each region) these problems can be eliminated.

6.3.2.31. The following lines are overloaded due to a single contingency:

Table 6.31 - Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 6A[24]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
4361	OUGHTRAGH	43619	OUGHTRAGH TEE	3	178.25	126
3581	LETTERKENNY	5361	TRILLICK	2	171.09	126
2571	FINGLAS RURAL	3761	MACETOWN	2	164.57	128
1651	CLAHANE	5281	TRALEE	1	157.52	126
3082	INCHICORE	4472	POOLBEG	1	145.48	267

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[24] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.7*–Portfolio 5, *Table 6.8*–Portfolio 6A

Table 6.31cont - Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Number of Violations	Max % Loading	Rating MVA
1651	CLAHANE	5261	TRIEN	1	137.34	126
2521	FLAGFORD	4981	SLIGO	1	133.89	126
2521	FLAGFORD	4981	SLIGO	1	133.62	126
1861	CARRICK ON SHANNON	2521	FLAGFORD	1	133.45	126
1861	CARRICK ON SHANNON	2521	FLAGFORD	1	133.25	126
86512	NEWRY 1B	90011	TANDRAGEE 1A	1	128.35	103
86511	NEWRY 1A	90011	TANDRAGEE 1A	1	128.35	103
4941	SHANNONBRIDGE	22419	DALLOW TEE	18	126.09	103
1201	ARTANE	2561	FINGLAS URBAN	1	124.03	120
1281	BALLYLICKEY	2221	DUNMANWAY	2	122.89	126
3082	INCHICOR	3122	IRISHTOWN	13	122.20	593
2202	DUNSTOWN	5202	TURLOUGH	2	119.92	351
5141	TARBERT	5261	TRIEN	6	119.82	128
3082	INCHICORE	4472	POOLBEG	1	116.21	267
2321	DRUMKEEN	3581	LETTERKENNY	5	116.00	126

Portfolio 6B – Winter Maximum – N-1 Contingency analysis

6.3.2.32. Undervoltages discussed above for Portfolio 2 remain in Portfolio 5.

6.3.2.33. A small number of single contingencies cause small overvoltages especially in South-West (especially Ballilickey), at Shelton and Arklow, in Co. Mayo and Co. Sligo, Dublin region. An addition of one 30 MVAr (nominal) reactor in these regions can eliminate these overvoltages.

6.3.2.34. Due to a single contingency transformers at Finglas, Inchicore, Woodland, Letterkenny, Shannonbridge, Trillick, and Castlereagh, are loaded more than 110%.

6.3.2.35. The following lines are overloaded due to a single contingency:

Table 6.32 -Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 6B[25]

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Violations	Max % Loading Cont.	Rating MVA
4361	OUGHTRAGH	43619	OUGHTRAGH TEE	3	209.32	126
3581	LETTERKENNY	5361	TRILLICK	2	171.58	126
1881	CHARLEVILLE	2881	GLENLARA	1	147.15	267

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[25] The overloaded lines for the intact system are not included in this table. These lines are given in *Table 6.9*–Portfolio 6B.

Table 6.32cont -Winter Maximum – Overloaded Lines- N-1 contingency analysis – Portfolio 6B

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Violations	Max % Loading Cont.	Rating MVA
3082	INCHICORE	4472	POOLBEG	1	144.61	518
2042	CORDUFF	2562	FINGLAS	1	139.05	518
2042	CORDUFF	2562	FINGLAS	1	139.05	126
1181	ARVA	1861	CARRICK ON SHANNON	10	139.02	103
4481	PORTLAOISE	22419	DALLOW TEE	97	134.34	120
1201	ARTANE	2561	FIN GLAS URBAN	1	134.31	128
1861	CARRICK ON SHANNON	10619	ARIGNA TEE	1	132.61	128
2521	FLAGFORD	4981	SLIGO	1	126.96	126
86512	NEWRY 1B	90011	TANDRAGEE 1A	1	125.31	103
86511	NEWRY 1A	90011	TANDRAGEE 1A	1	125.31	103
1631	CORDERRY	10619	ARIGNA TEE	1	124.66	164
1361	BALLYDINE	2001	CULLENAGH	12	121.74	126
3501	LANESBORO	4001	MULLINGAR	15	120.26	126
2202	DUNSTOWN	5202	TURLOUGH	2	119.46	351
3082	INCHICORE	4472	POOLBEG	1	117.99	267
3842	MAYNOOTH	5202	TURLOUGH	1	117.38	351
1661	CASTLEBAR	1821	CLOON	2	116.71	126
1441	BANDON	2221	DUNMANWAY	1	115.46	126

7 Network Reinforcements – Task 2

7.1. It should be emphasised that the network reinforcements proposed in this section are:

- not all required reinforcements that will guarantee N-1 security of the Irish electricity system under all plausible conditions but,

- the ones that can eliminate only the identified network constraints caused by renewable generation which is the main objective of this study.

7.2. The network reinforcements identified in Task1 (Section 5) are refined through Task2. The main conclusions of this transition phase from Task 1 to Task 2 are:

- not too many new network reinforcement are added to the final lists of the network reinforcements moving from Task 1 to Task 2;

- the initial points for all portfolios and all operating regimes in Task 2 taken as the output of Task 1 were far from the AC power flow feasibility boundary due to a serious lack of reactive power support caused by 'replacing' conventional units electrically close to load centres with wind generation electrically far from these centres and with limiting reactive power capability;

- for certain contingencies AC power flow was not able to converge. Further in depth investigations of these cases show that many of these divergence cases are caused by a loss of the main reactive power feeders, especially those related to the Dublin or South-West regions and in some cases for the Northern Ireland region. A lesson learned from these non-convergence cases is that certain number of units will need to be run in these regions to ensure power flow convergence and voltage compliance.

7.3. A summary of the proposed network reinforcements in terms of the new and uprated 220 kV, 275 kV and 110 kV total line lengths is given in *Table 7.1.* Portfolio 6A required almost 500 km of new 220/275 kV lines almost 130 km more than Portfolio 5 and Portfolio 6B (370 km) and 220km more than Portfolio 2,3 and 4. The total line length in Portfolio 6A is the biggest considering that the additional lengthy 220 kV lines are required to transfer wind power from the offshore wind farms connected to Ballilickey and Shelton Abbey.

7.4. Portfolio 6B requires the largest number of new and uprated lines (in terms of the total line length) considering that this portfolio is additionally studied only in Task 2 and its initial point for Task 2 analysis was the reinforced Portfolio 5 network from the Task 1 work.

Table 7.1- Total line lengths for new and uprated lines

	Portfolio 6A	Portfolio 6B	Portfolio 5	Portfolios 4,3,2	Portfolio 1
Total length (km) of new 220 or 275 kV lines (km of double circuits)	498 (254)	370 (262)	370 (227)	282 (130)	n.a.
Total length (km) of new 110 kV lines	255	294	228	182	37.4
Total length (km) of uprated 110 kV lines	216	253	190	191	37.4

7.5. For almost all proposed new lines there is at least the existing 110 kV route. It should be pointed out that all existing 110 kV lines are retained and the existing 110 kV corridors would need to be extended at least. There is several exceptions such us: the 275 kV line Trillick to Coolkeeragh or the 220 kV line Clonkeen to Glenlara or the 110 kV line Macroom to Trabeg where the new corridors needs to be built.

7.6. The existing 220 kV line Tarbert to Clashavoon is split into several sections, with new 220 kV substations inserted between these sections. It is estimated that up to 50% of the costs of a new line can be required in this case for re-routing.

7.7. The network reinforcement costs are calculated using the following facts/assumptions:

i. In-house unit cost data was used to calculate overall network reinforcements costs. The unit costs exclude civil works land purchasing costs. This data is given in *Table 7.2*.

ii. The final reinforcement lists given in *Appendix G* for each portfolio are used to calculate the reinforcement costs. The cost calculation is a simple calculation based on the line length, the number of transformers, bays and substations. To distinguish new and uprated lines an ‘uprating cost correction factor’ (see *Table 7.2*) is used.

iii. Additional reactive power support given in *Table 6.1* and *Table 6.2* is considered in the cost calculation using a price of €75/kVar.

iv. The costs of small capacitors/reactors proposed to eliminate undervoltages/overvoltages in some portfolios are ignored considering that the wind farms connected directly to the transmission system should have such reactive capability.

v. In Northern Ireland for all 275 kV lines it was assumed that double circuit 275 kV lines would be built to be consistent with the current practice.

vi. The asset financing costs are not taken into account.

7.8. The cost results shown in *Figure 7.1* show that the network reinforcement cost increases with the level of renewable generation. Thus, the smallest reinforcement costs are for Portfolio 1 (€92M) taking into account that the considered renewable power output for this portfolio is the smallest (about 2.2 GW). On the other hand, the considered renewable power output for Portfolio 6A is about 6.9 GW and the estimated reinforcement costs are the highest ones (€1,293M).

7.9. A significant portion of the network reinforcement costs in Portfolio 2 to Portfolio 6 are the network reinforcement costs for the 220/275 kV network - between 56% and 58%, the cost of additional reactive power support is between 15% and 18%, the network reinforcement costs for 110 kV network are between 13% and 19%. The cost spread is shown only for Portfolio 6A and Portfolio 4 in *Figure 7.2.*

7.10. The cost spread[26] for different regions is given in *Table 7.3,Table 7.4, Table 2.1,Table 7.6*for Portfolio 6A, Portfolio 6B, Portfolio 5 and Portfolios 2,3,4, respectively. For this particular exercise Ireland is split into several different regions in order to group the network reinforcements geographically close to each other. Thus, the first region encompasses

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[26] It should be pointed out that cost spread does not include additional reactive power support. To determine the regional and network locations of this support more comprehensive studies based on the optimal placement procedures would be required.

Co.Mayo, Co.Sligo and Co. Donegal. The second region is Northern Ireland, the third region is South-West, the fourth region is South-East, while the fifth region includes the network reinforcements in Co. Leitrim and Co. Roscommon ('neighbouring lines' to Flagford substation).

Table 7.2 - Unit cost data

Unit	Cost (€)
Transformers 220(or 275)/110 kV	3,000,000
Substation 220 or 275 kV	5,000,000
Bay 220 (or 275) kV	1,540,000
Bay 110 kV	700,000
Standard 110 kV line per km	273,000
Standard single circuit 220 (or 275) kV line per km	840,000
Uprating cost correction factor	1
Capacitor cost/KVAr	75

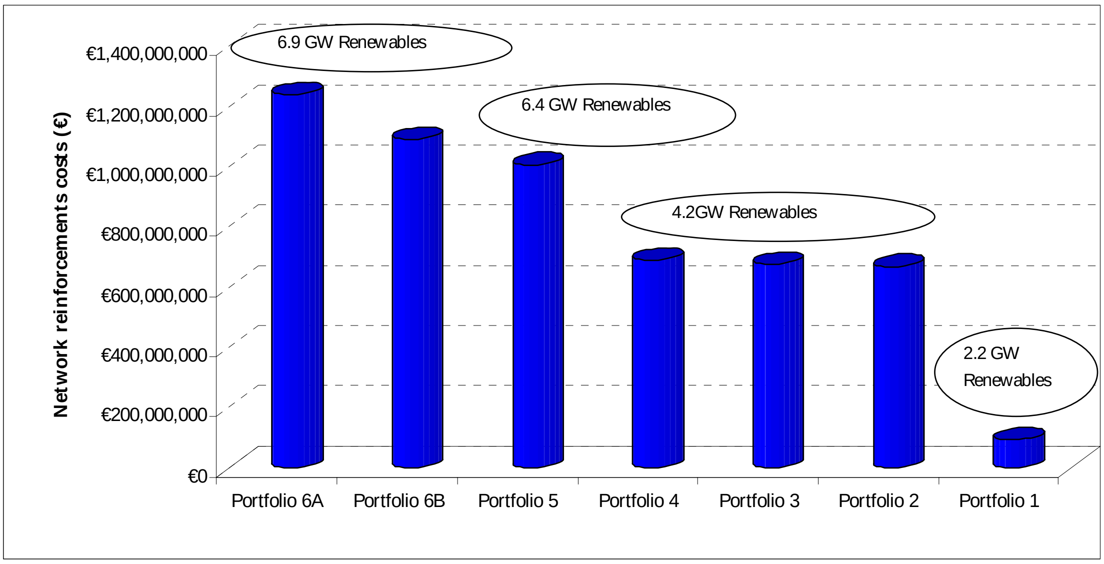
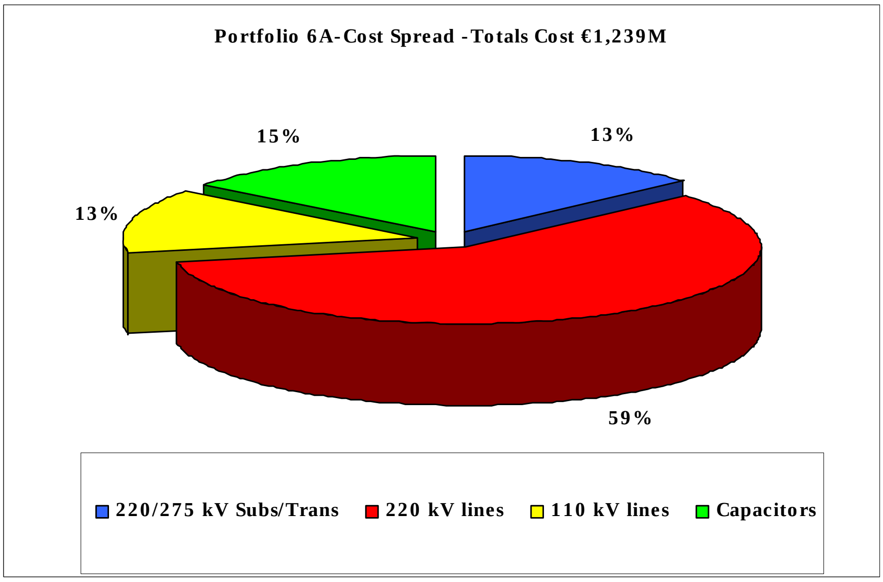


Figure 7.1-Network reinforcement costs



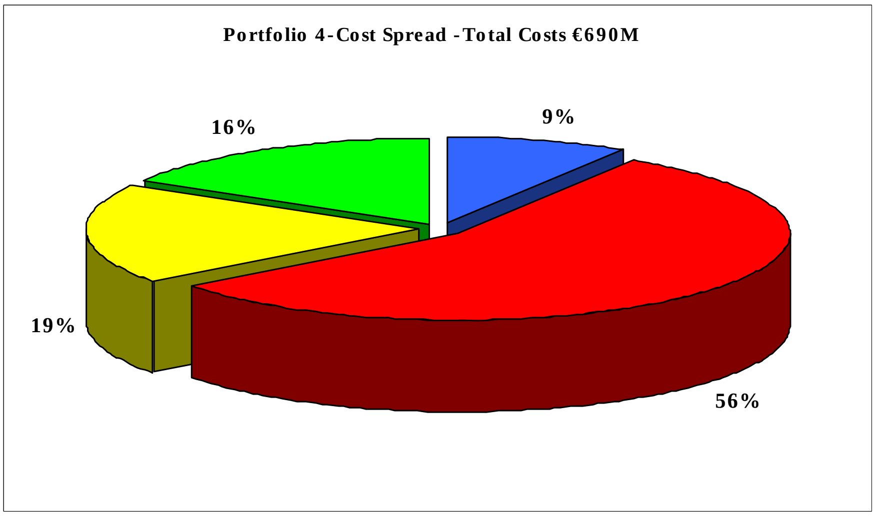


Figure 7.2 Portfolio 6A and Portfolio 4 cost spread

Table 7.3 - Cost components –Portfolio 6A

	Transformers	220/275 kV lines	110 kV lines	Total
Co.Mayo Sligo Donegal	€66,920,000	€274,176,000	€46,866,120	€387,962,120
Northern Ireland	€25,720,000	€234,640,000	€27,142,500	€287,502,500
South-West	€56,440,000	€168,000,000	€38,907,400	€263,347,400
South-East	€15,480,000	€51,520,000	€3,346,000	€70,346,000
Flagford	€0	€0	€50,182,720	€50,182,720
Total	€164,560,000	€728,336,000	€166,444,740	€1,059,340,740

Table 7.4 -Cost components –Portfolio 6B

	Transformers	220/275 kV lines	110 kV lines	Total
Co.Mayo Sligo Donegal	€61,680,000	€256,648,000	€61,970,790	€380,298,790
Northern Ireland	€25,720,000	€258,720,000	€20,545,000	€304,985,000
South-West	€35,960,000	€69,020,000	€40,940,900	€145,920,900
South-East	€0	€22,400,000	€4,566,800	€26,966,800
Flagford	€0	€0	€60,146,870	€60,146,870
Total	€123,360,000	€606,788,000	€188,170,360	€918,318,360

Table 7.5 -Cost components-Portfolio 5

	Transformers	220/275 kV lines	110 kV lines	Total
Co.Mayo Sligo Donegal	€56,440,000	€219,128,000	€42,140,140	€317,708,140
Northern Ireland	€25,720,000	€234,640,000	€31,227,000	€291,587,000
South-West	€35,960,000	€60,200,000	€38,421,600	€134,581,600
South-East	€0	€22,400,000	€4,566,800	€26,966,800
Flagford	€0	€29,120,000	€26,662,020	€55,782,020
Total	€118,120,000	€565,488,000	€143,017,560	€826,625,560

Table 7.6 -Cost components –Portfolios 2,3,4

	Transformers	220/275 kV lines	110 kV lines	Total
Co.Mayo Sligo Donegal	€20,480,000	€96,040,000	€31,927,420	€148,447,420
Northern Ireland	€20,480,000	€210,560,000	€0	€231,040,000
South-West	€20,480,000	€57,120,000	€94,039,050	€171,639,050
South-East	€0	€22,400,000	€4,566,800	€26,966,800
Flagford	€0	€0	€0	€0
Total	€61,440,000	€386,120,000	€130,533,270	€578,093,270

7.11. The incremental costs are shown in *Figure 7.3* as a percentage of the reinforcement costs of the most expensive portfolio – Portfolio 6A. It is clear that increasing the wind power installed capacity from 2GW in Portfolio 1 to 4GW in Portfolios 2,3,4 will be the most demanding step in terms of network reinforcements. To accommodate the additional 2GW (an increment from Portfolio 2,3,4 to Portfolio 5) of wind generation in Portfolio 5 will require significant network reinforcements (€339M). It should be pointed that the extent of the next increment (Portfolio 5 to Portfolio 6) is masked by a significant wind curtailment assumed in Portfolio 6. The results of the randomisation studies given in *Section 4* indicate that accommodating more than 6.9 GW of renewable generation in this portfolio would double the network constraint identified for example for Portfolio 5. The difference in the network reinforcement costs between Portfolio 6A and Portfolio 6B is due to additional 220 kV line and the corresponding infrastructure at Ougthragh, Ballilickey and Shelton Abbey where big offshore wind farms can be connected.

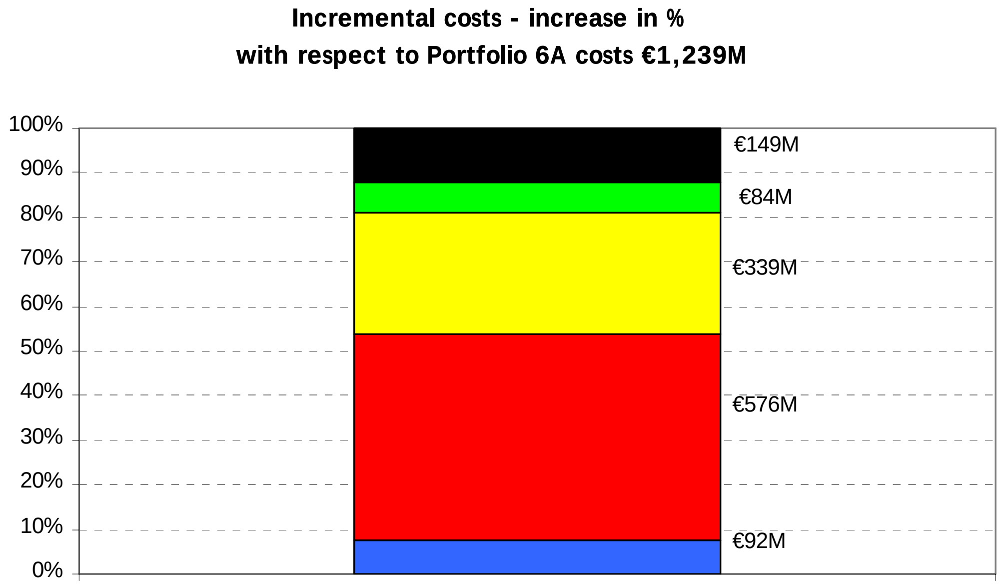


Figure 7.3– Incremental portfolio costs

7.12. The spread of regional costs for the first four regions is shown in *Figure 7.4*.It is clear that the extent of the network reinforcements in the first region (Co.Mayo, Co. Sligo and Co.Donegal) is significantly larger than for the other regions. For example in Portfolio 5 – 6GW installed wind capacity the total costs calculated for the first region are €318M, for the second region €292M, for the third region €135M and for the last two regions less €27M and €56M, respectively. The lowest extent of the network reinforcements is observed for the South-East region.

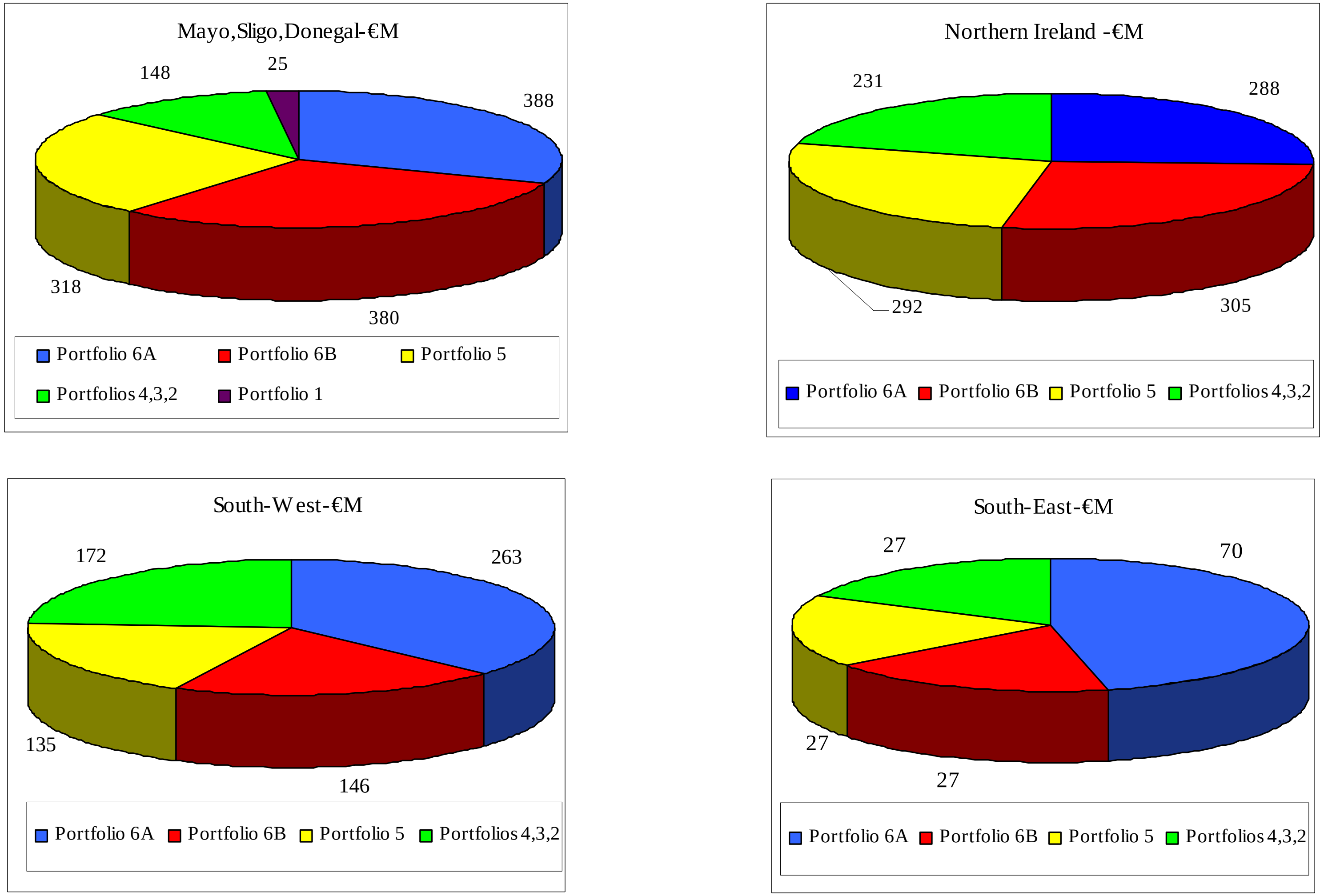


Figure 7.4 – Spread of regional network reinforcement costs

8 Conclusions and Future Work

8.1. The main objective of Work-stream 3 All Island Grid Study was to investigate the extent of network development for a range of renewable generation penetration levels based on the generation portfolios developed by Work-stream 2a.

8.2. The focus of this work-stream was on the transmission network reinforcements that might be required in Ireland by 2020 in order to accommodate new renewable generation.

8.3. WS3 comprised two principal tasks:

- **Task 1** – DC load-flow analyses to identify network flow constraints and bottlenecks and to propose a set of network reinforcements to eliminate these constraints. The analysis is fully based on DC load flow and use of the following calculation techniques:
    - Security Constrained Optimal Power Flow (SCOPF) –to distinguish the line overloads caused by renewable sources from those caused by demand and/or conventional generation and to identify the nodal candidates for voltage uprating (from 110kV to 220 kV or 275 kV).
    - Random sampling – whose objective was to investigate the impact of wind penetrations and forced generation outages on the network conditions for a significant number of randomly created operational scenarios.
- **Task 2** – AC-load-flow analyses to refine the results of Task 1, and to include the consideration of system reactive support requirements. It was originally intended to use the ASSESS software tool to undertake a comprehensive security assessment in this task. However, the optimal power flow used by this tool was not able to successfully deal with voltage and reactive power issues. This caused a shift in Task 2 analysis more toward voltage security. TNEI therefore used alternative in-house tools to undertake voltage security analysis.

8.4. The Task 1 studies of the three different operational regimes: winter peak, summer maximum and summer minimum showed that wind resources which are ‘electrically far’ from 220 kV 275 kV and 400 kV network cause a significant loading of the 110 kV network. All ‘wind rich’ areas have little demand comparing to their installed wind capacities and most of the wind power has to be exported to the other system parts through the 110 kV network.

8.5. The overloaded lines are mainly located in the areas where a significant wind installed capacities are anticipated such as Co. Mayo, Co. Sligo and Co. Donegal, South-West, Northern Ireland, Co. Waterford and Co. Wexford. The higher is the wind penetration in these areas the bigger is the extent of the problem in terms of the number of overloads. In addition to these four regions it was found that in Portfolio 5 and Portfolio 6 a significant number of the 110 kV lines connected to the Flagford substation becomes overloaded.

8.6. The Task 1 studies indicated that for Portfolios 2,3 and 4 (wind installed capacity is 4000MW), the transmission network would suffer overloads on 30-40 circuits. For Portfolio 5 (wind installed capacity is 6000MW) the system would suffer overloads on 50-60 circuits. For Portfolio 6 (wind installed capacity is 8000MW), it was found that for renewable penetration of up to 6900MW, the situation is essentially as for Portfolio 5. For penetrations over 6,900MW, the number of overloaded circuits becomes unmanageably large. This level of wind penetration of 6,900 MW is therefore designated as a ‘knee’ point. For the penetrations larger than the ‘knee point’ the number of overloads was almost doubled with respect to Portfolio 5 for a significant number of random operational scenarios.

8.7. It was found through the Task 1 network reinforcement studies that for the renewable penetrations larger than the identified ‘knee point’ the network reinforcement problem becomes in essence a network re-design problem which is out of the scope of this study. Therefore, for Portfolio 6 the network reinforcement studies were carried out only for up to 6,900 MW of wind renewable penetration.

8.8. The following 110kV nodes were identified in Task 1 as suitable candidates for upgrade to 220kV (this would involve the construction of new 220kV infrastructure): Bellacorick, Cunghill, Castlebar, Letterkenny, Trillick, Sorne Hill, Clonkeen, Coomagearlaghy, Glanlee, Ougtragh, Macroom, Charleville, Omagh.

8.9. The network reinforcement carried out in Task 1 is an 'incremental' network reinforcement approach which consists of 'backward' and 'forward' phase. The 'backward' phase starts with Portfolio 6A and identify all necessary network reinforcements for this most onerous portfolio. The required reinforcements for less onerous portfolios are determined removing one by one 'unnecessary' reinforcement from the previous step. The 'forward' phase identifies firstly all necessary reinforcements for the least onerous portfolio. The required reinforcements for more onerous portfolios are determined adding one by one 'necessary' reinforcement. A final set of necessary network reinforcements was then found from these two phases.

8.10. A summary of the proposed network reinforcements in terms of the new and uprated 220 kV, 275 kV and 110 kV total line lengths is given in *Table 7.1.* It can be seen in this table that Portfolio 6A required almost 500 km of new 220/275 kV lines almost 130 km more than Portfolio 5 and Portfolio 6B (370 km) and 220km more than Portfolio 2,3 and 4.

8.11. For almost all proposed new 220/275 kV lines the existing 110 kV corridors would need to be extended at least. There are several exceptions such as: the 275 kV line Trillick to Coolkeeragh or the 220 kV line Clonkeen to Glenlara or the 110 kV line Macroom to Trabeg where the new corridors needs to be built.

8.12. The existing 220 kV line Tarbert to Clashavoon is split into several section with new 220 kV substations inserted between these sections. It is estimated that up to 50% of the costs of a new line can be required in this case for the re-routing required for the new sections.

8.13. The reinforced networks as a direct output of Task 1 analysis were used as the starting points of Task 2 analysis. The network reinforcements identified in Task1 are refined through Task 2. The main conclusions of the transition phase from Task 1 to Task 2 are:

- The main advantage of the 'two-tasks(Task 1 and Task 2) concept' was that not too many new network reinforcement are added to the final lists of the network reinforcements moving from Task 1 to Task 2. This means that the addition of new lines and the uprating of the existing circuits was mainly guided by MW flows.

- The main disadvantage of the 'two-tasks concept' was that starting points for all portfolios and all operating regimes in Task 2 were far from the AC power flow feasibility boundary due to a serious lack of reactive power support.

8.14. The Task 2 analysis showed that one of the main challenges for the 2020 Irish power system will be voltage and reactive power control considering that a significant number of conventional units capable of providing reactive power and located electrically close to load centres will be replaced by wind generation located electrically far from the load centres with limited capability to provide reactive power.

8.15. To ensure that the Irish 2020 power system can meet the voltage requirements stipulated by existing planning standards up to 2400 MVAr of additional reactive power compensation will be required. Reactive support will be mainly required in the following regions North-East (Cavan, Louth, Gorman), Dublin region, South-West, Northern Ireland.

8.16. The locations of new capacitors were determined based on the calculation of voltage stability indices. It should be noted that:

- the placement of the new capacitors is not based on an optimisation approach and

- there is no distinction between 'static' and 'dynamic' reactive power requirements in the undertaken calculation of voltage stability indices.

8.17. Network reinforcement costs were calculated using in-house unit costs data. The cost calculation takes into account:

- substation and bay costs,
- costs of building and uprating 220 kV, double circuit 275 kV, and 110 kV lines,
- costs of transformers and
- costs of capacitors

and does not take into account:

- land purchasing and civil work costs and
- the asset financing costs.

8.18. The cost calculation showed that the network reinforcement cost increases with the level of renewable generation. Thus, the smallest reinforcement costs are for Portfolio 1 (€92M) taking into account that the considered renewable power output for this portfolio is the smallest (about 2.2 GW). On the other hand, the considered renewable power output for Portfolio 6A is about 6.9 GW and the estimated reinforcement costs are the highest ones (€1,239M).

8.19. The network reinforcement costs for Portfolio 6B are €1,090M, for Portfolio 5 are €1,006M, while for Portfolio 2,3 and 4 these costs vary between €668M and €690M.

8.20. A significant portion of the network reinforcement costs in Portfolio 2 to Portfolio 6 is associated with the construction of new 220/275 kV network. The cost of additional reactive power support is between 15-18%, and the network reinforcement costs for 110 kV network are between 13% and 19%.

8.21. To calculate the regional spread of the network reinforcement costs, Ireland was split into the following regions:

- Co. Mayo, Co. Sligo and Co. Donegal.
- Northern Ireland,
- South-West,
- South-East,
- Co. Leitrim and Co. Roscommon only for Portfolio 5 and Portfolio 6.

8.22. It is clear that the extent of the network reinforcements in the first region (Co.Mayo, Co. Sligo and Co.Donegal) is significantly larger than for the other regions. For example in Portfolio 5 – 6GW installed wind capacity the total costs calculated for the first region are €318M, for the second region €292M, for the third region €135M and for the last two regions less €27M and €56M, respectively.

8.23. The biggest step in terms of the network reinforcements is the move from the wind power installed capacity of 2GW in Portfolio 1 to 4GW in Portfolios 2,3,4 with incremental cost of €576M. To accommodate the additional 2GW of wind generation in Portfolio 5 will require a significant incremental costs of €339M.

8.24. There are several suggestions in terms of the recommended future studies:

1. Instead of assuming firm connections for all wind farms and other renewables ‘time unlimited’ non-firm connections can be considered in order to avoid the most expensive

network reinforcements. Future studies could be carried out to investigate the advantages and disadvantages of such 'time unlimited' non-firm wind connections.

2. Further studies related to the optimal placement of the additional reactive power support could be required to determine the best locations for the additional reactive power support and the optimal split between 'static' and 'dynamic' reactive power requirements. In our view these studies should be given high priority.

3. Transient stability studies to investigate angle and voltage stability of the future 2020 Irish electricity system.

4. Fault calculation studies – to investigate the fault level issues for the future 2020 Irish electricity system.

Appendix-A

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Table A 1–Wind farm install capacities (MW) - grid locations

BUS NAME (110 KV)	BUS ID	P6A	P6B	P5	P4	P3	P2	P1
AGANNYGAL	1071	60	89.75	89.75	60	60	60	60
ANNER	1101	27.72	27.72	0	0	0	0	0
ARDNACRUSHA	1021	82.15	69.15	13.71	10.71	10.71	10.71	10.71
ARIGNA	1061	38.72	38.72	11	11	11	11	11
ARKLOW	1121	122.2	122.2	122.2	122.2	122.2	122.2	117.7
ATHEA	1131	51	51	51	51	51	51	51
ATHLONE	1141	0	4.25	4.25				
BALLYCADDEN	1331	18	18	0	0	0	0	0
BALLYDINE	1361	79.44	79.44	79.44	24	24	24	0
BALLYLICKEY	1281	180.24	180.24	55.5	55.5	55.5	55.5	28.1
BALLYMEN	71011	109.8	109.8	109.8	73	73	73	49.5
BALLYNAH	72511	13.86	13.86	13.86	0	0	0	0
BANDON	1441	4.5	4.5	4.5	4.5	4.5	4.5	4.5
BELLACORICK	1401	265.13	265.13	237.41	223.55	223.55	223.55	207.45
BINBANE	1341	151.33	154.53	99.09	51.76	51.76	51.76	43.86
BOOLTIAGH	1251	19.5	19.5	19.5	19.5	19.5	19.5	19.5
BUTLERSTOWN	1481	17.86	17.86	4	4	4	4	1.7
CAHIR	1721	173.38	201.1	62.5	0	0	0	0
CARRICK ON SHANNON	1861	3	7.25	7.25	0	0	0	0
CARLOW	1901	62.97	67.47	39.75	35.25	35.25	35.25	7.55
CASTLEBAR	1661	132.64	132.64	49.48	49.48	49.48	49.48	24.2
CATHLEEN'S FALLS	1701	96.13	96.63	96.63	96.13	96.13	96.13	10.73
CHARLEVILLE	1881	12.5	49.1	49.1	12.5	12.5	12.5	0
CLAHANE	1651	37.8	37.8	37.8	37.8	37.8	37.8	37.8
CLASHAVOON	1601	87	87	87	30	30	30	0
CLIFF	1761	13.86	13.86	0	0	0	0	0
COLERAINE	75010	20	20	20	20	20	20	20
COOMACHEO	1771	41.2	41.2	41.2	41.2	41.2	41.2	41.2
COOMAGEARLAHY	1971	167.5	167.5	167.5	167.5	167.5	167.5	42.5
CORDERRY	1631	177.935	186.935	103.775	63.25	63.25	63.25	32.05
CORRACLASSY	1981	27.72	27.72	0	0	0	0	0
CRANE	1841	268.05	159.05	145.19	102.69	102.69	102.69	36.49
CREAGH	75810	10.5	10.5	10.5	10.5	10.5	10.5	0
CULLENAGH	2001	0	36	36	0	0	0	0
CUNGHILL	1931	231.7	231.7	23.8	23.8	23.8	23.8	23.8
DALLOW	2241	6.8	6.8	6.8	6.8	6.8	6.8	6.8
DALTON	2281	2.55	2.55	2.55	2.55	2.55	2.55	0
DONEGALL(BELFAST)f	76512	13.86	13.86	0	0	0	0	0
DOON	2161	12	33	33	12	12	12	12
DRUMKEEN	2321	71	71	71	71	71	71	71
DRYBRIDGE	2181	7	7	7	1.7	1.7	1.7	1.7
DUNDALK	2101	7.5	20.85	20.85	7.5	7.5	7.5	7.5
DUNGANNON	77510	0	40.5	46	16	16	16	
DUNGARVAN	2141	95.98	95.98	54.4	35	35	35	0
DUNMANWAY	2221	183.11	183.11	113.81	113.81	113.81	113.81	36.51
ENNIS	2361	47.68	83.68	83.68	0	0	0	0
ENNISKILLEN	79010	147.25	210.5	210.5	117.25	117.25	117.25	95.25
FASSAROE EAST	2481	75	24	48	0	0	0	0
FASSAROE WEST	2491	75	24	0	0	0	0	0
GALWAY	2781	275.625	338.925	338.925	133.125	133.125	133.125	3.975

Table A1cont -Wind farm installed capacities (MW) - grid locations (Portfolios)

BUS NAME (110 KV)	**BUS ID**	**P6A**	**P6B**	**P5**	**P4**	**P3**	**P2**	**P1**
GLANLEE	2731	29.8	29.8	29.8	29.8	29.8	29.8	29.8
GLENLARA	2881	204.16	273.46	190.3	137.3	137.3	137.3	36.5
GOLAGH	2801	28.86	28.86	15	15	15	15	15
IKERRIN	3101	25.41	82.81	68.95	5.1	5.1	5.1	5.1
KILKENNY	3261	36.61	36.61	22.75	8.75	8.75	8.75	0
KILTOY	3361	55.44	55.44	13.86	0	0	0	0
KNOCKERAGH	3301	50.9	92.39	92.39	45.9	45.9	45.9	9.35
LANESBORO	3501	4.5	4.5	4.5	0	0	0	0
LARNE MAIN	83011	13.75	13.75	13.75	13.75	13.75	13.75	13.75
LETTERKENNY	3581	83.16	83.16	83.16	83.16	83.16	83.16	41.96
LIMAVADY	83510	142.08	142.08	31.2	31.2	31.2	31.2	31.2
LISAGHMORE	84411	201.78	201.78	160.2	160.2	160.2	160.2	133.2
LISDRUM	3561		30	30				
LISHEEN	3621	55	55	55	0	0	0	0
LODGEWOOD	3641	19.5	19.5	37.5	37.5	37.5	37.5	19.5
LOGUESTOWN	84511	187.6	0	0	0	0	0	0
MACROOM	3881	64.75	64.75	64.75	64.75	64.75	64.75	15
MALLOW	4021	26.85	42.85	42.85	20	20	20	20
MEATH HILL	3821	30	30.5	30.5	15	15	15	15
MEENTYCAT	4071	14	14	14	14	14	14	14
MIDLETON	3801	18	21.4	21.4	0	0	0	0
MONEYPOINT	3941	21.9	21.9	21.9	21.9	21.9	21.9	21.9
MOY	4041	109.01	138.91	138.91	95.15	95.15	95.15	21.2
MULLAGHARIN	4061	150	0	0	0	0	0	0
MULLINGAR	4001	18	152	4.5				
NENAGH	4261	219.56	518.8	152.81	136.4	136.4	136.4	0
OMAGH	87510	359.8	175.32	502.8	300.3	300.3	300.3	49.4
OUGHTRAGH	4361	166.32	65.5	64.44	0	0	0	0
RATHKEALE	4681	65.5	103.62	65.5	22.5	22.5	22.5	12.5
RATRUSSAN	4781	100.62	2.55	100.62	100.62	100.62	100.62	94.8
RICHMOND	4701	2.55	30.72	2.55	2.55	2.55	2.55	0
SHANKILL	4961	33.72	69.3	6	6	6	6	6
SHELTON ABBEY	4901	406.3	44.31	0	0	0	0	0
SLIGO	4981	36.66	8.5	30.45	19.8	19.8	19.8	0
SOMERSET	5001	8.5	170.13	8.5	8.5	8.5	8.5	7.65
SORNE HILL	4991	170.13	88.6	128.55	59.25	59.25	59.25	32.1
STRABANE	89510	47.6	97.02	88.6	47.6	47.6	47.6	47.6
STRATFORD	5061	97.02	43.86	0	0	0	0	0
TAWNAGHMORE	5241	43.86	79.2	30	30	30	30	0
THORNSBERRY	5321		112.86	79.2				
THURLES	5301	103.86	94.39	99	86	86	86	0
TIPPERARY	5381	55.44	5.94	38.95	0	0	0	0
TONROE	5341	5.94	162.27	5.94	5.94	5.94	5.94	5.94
TRALEE	5281	162.27	227.59	148.41	138.41	138.41	138.41	62.86
TRIEN	5261	227.59	163.14	227.59	223.59	223.59	223.59	36.09
TRILLICK	5361	163.14	22.2	38.4	34.4	34.4	34.4	34
TULLABRACK	5221	22.2	4.25	22.2	22.2	22.2	22.2	12.6
WATERFORD	5441	4.25	0	4.25	4.25	4.25	4.25	0
WEXFORD	5501	80.58	80.58	39	39	39	39	39
	TOTALS:	8000	8000	6000	4000	4000	4000	2000

Appendix-B

Disclaimer

The purpose of the network diagrams presented in the following appendices is only to illustrate the envisaged network reinforcements between 2007 and 2020, intact system network flows, the identified network overloads and the proposed network reinforcements. It should be pointed out that the network data used for the study were obtained directly from the TSOs and it might be some discrepancies between this data and the network diagrams herein.

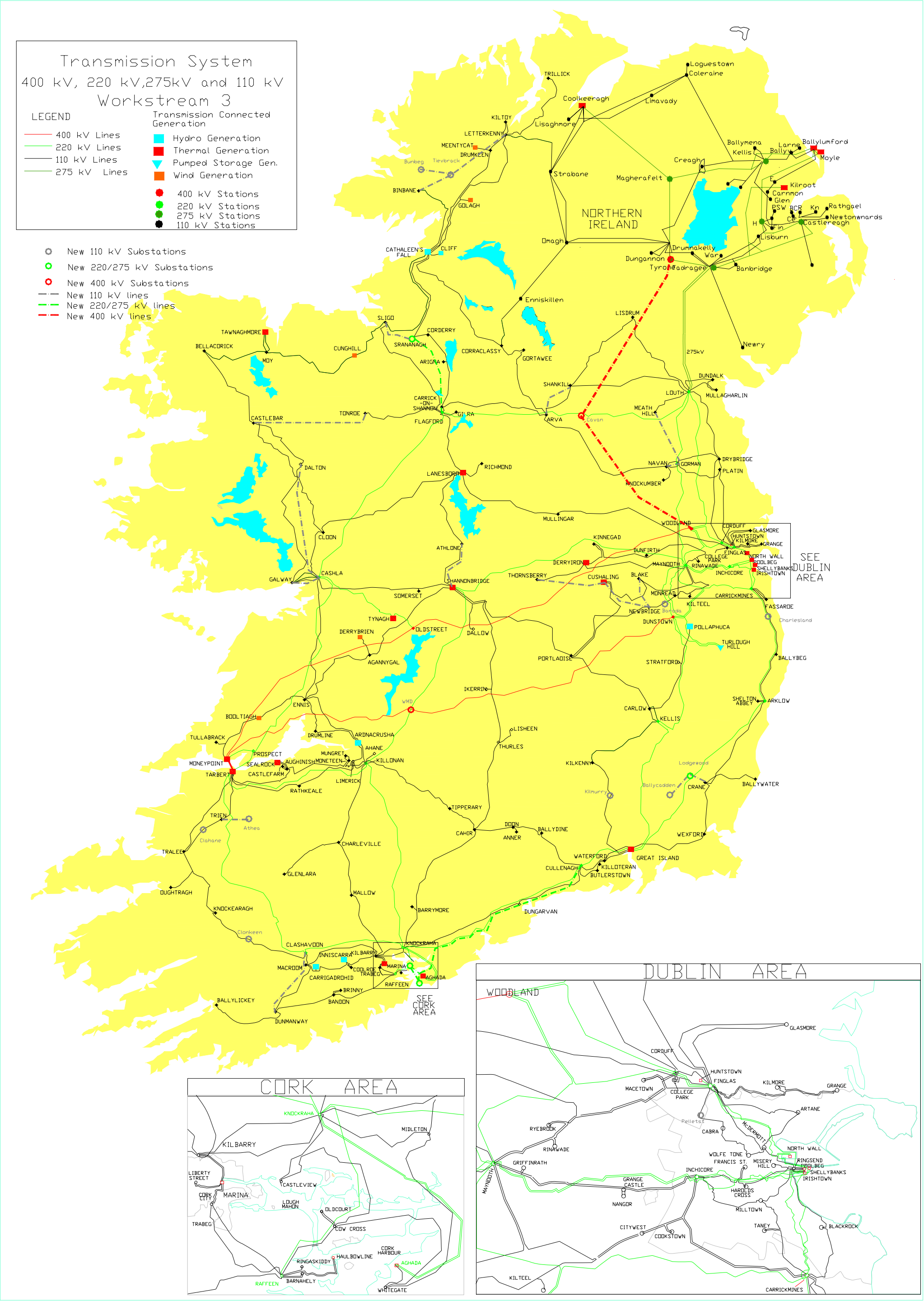


Figure B 1- Envisaged network reinforcements between 2007 and 2020

Appendix-C

Disclaimer

The purpose of the network diagrams presented in the following appendices is only to illustrate the envisaged network reinforcements between 2007 and 2020, intact system network flows, the identified network overloads and the proposed network reinforcements. It should be pointed out that the network data used for the study were obtained directly from the TSOs and it might be some discrepancies between this data and the network diagrams herein.

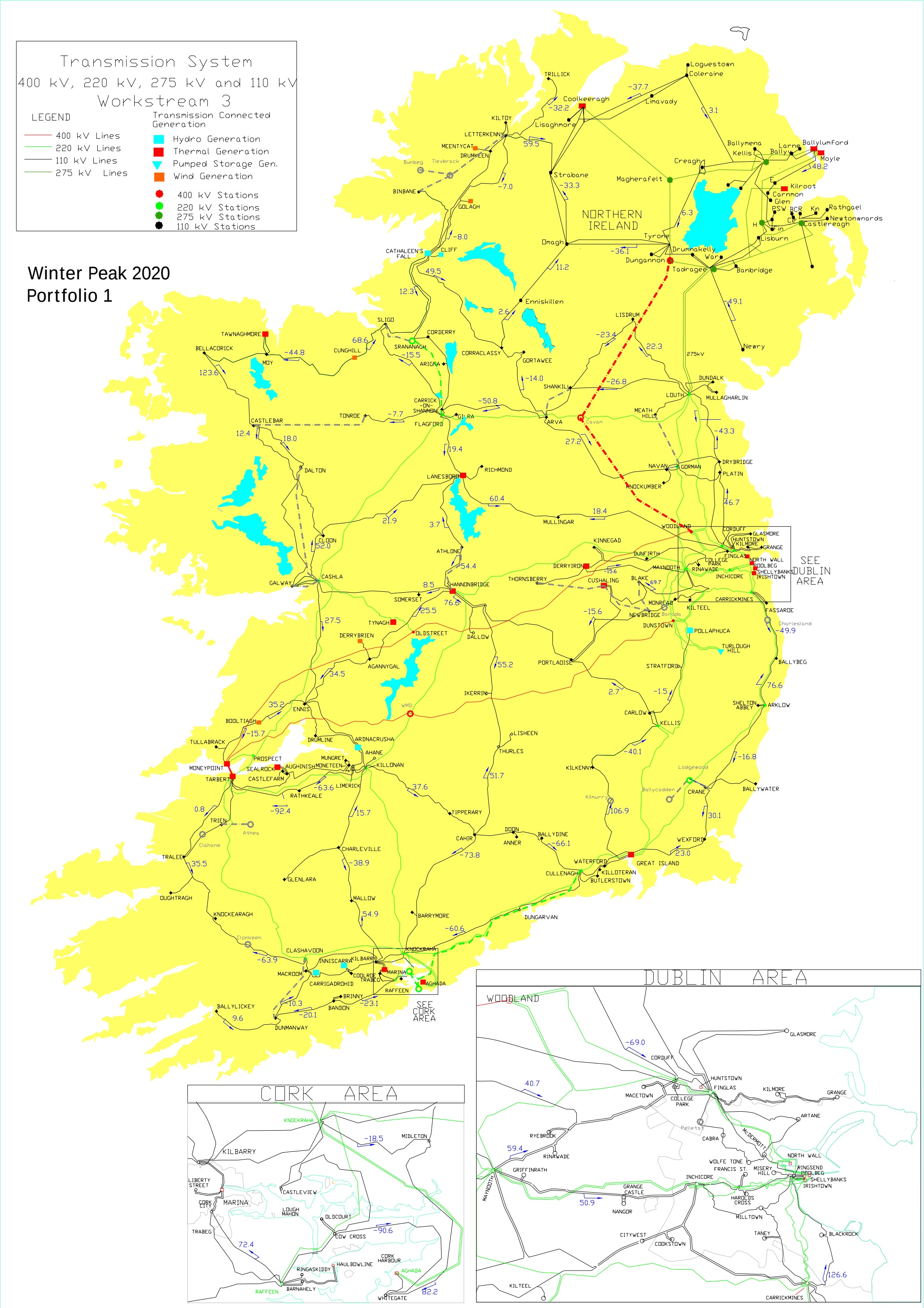


Figure C1- Winter Peak – Intact System Flows – Portfolio 1

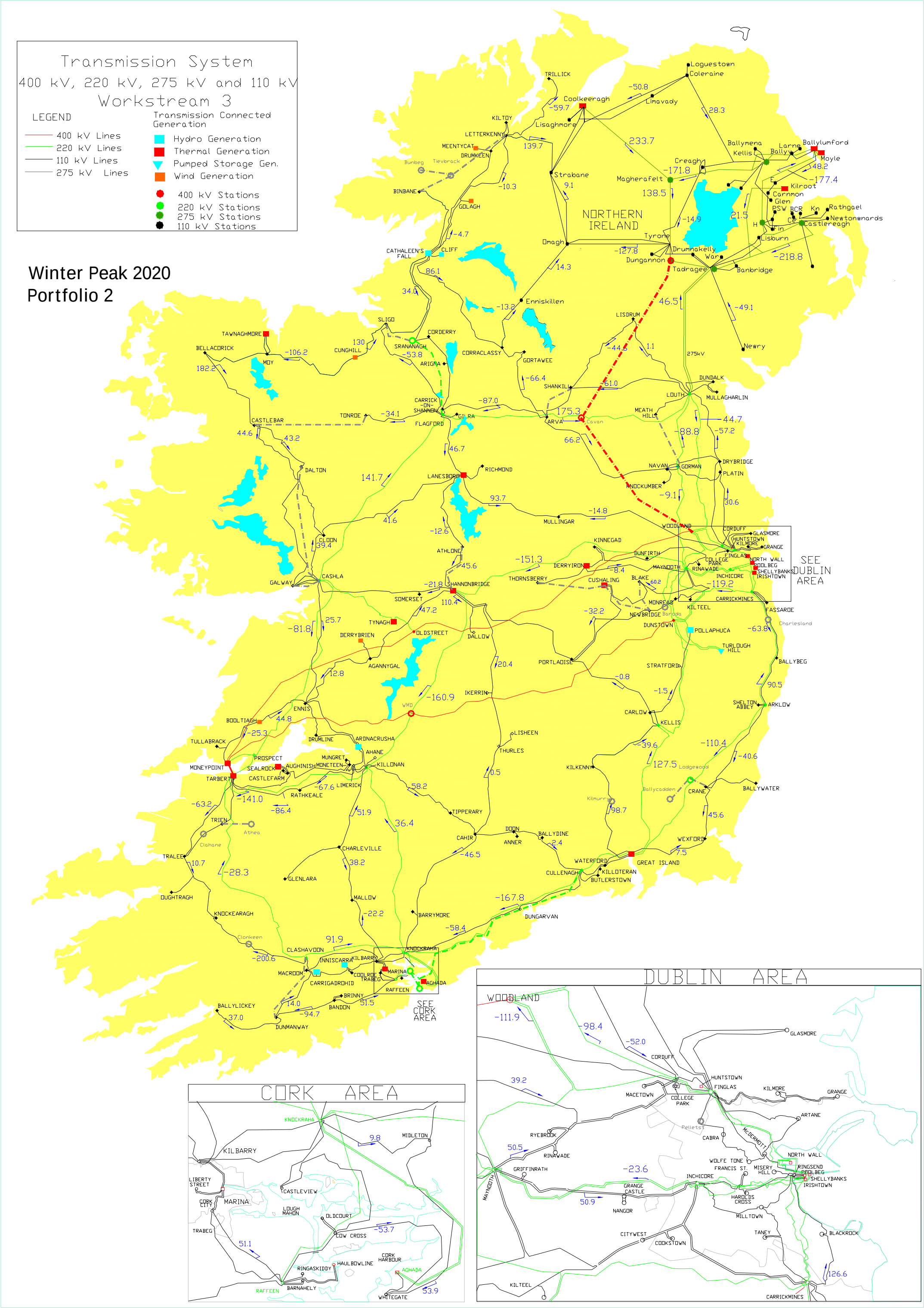


Figure C 2- Winter Peak – Intact System Flows – Portfolio 2

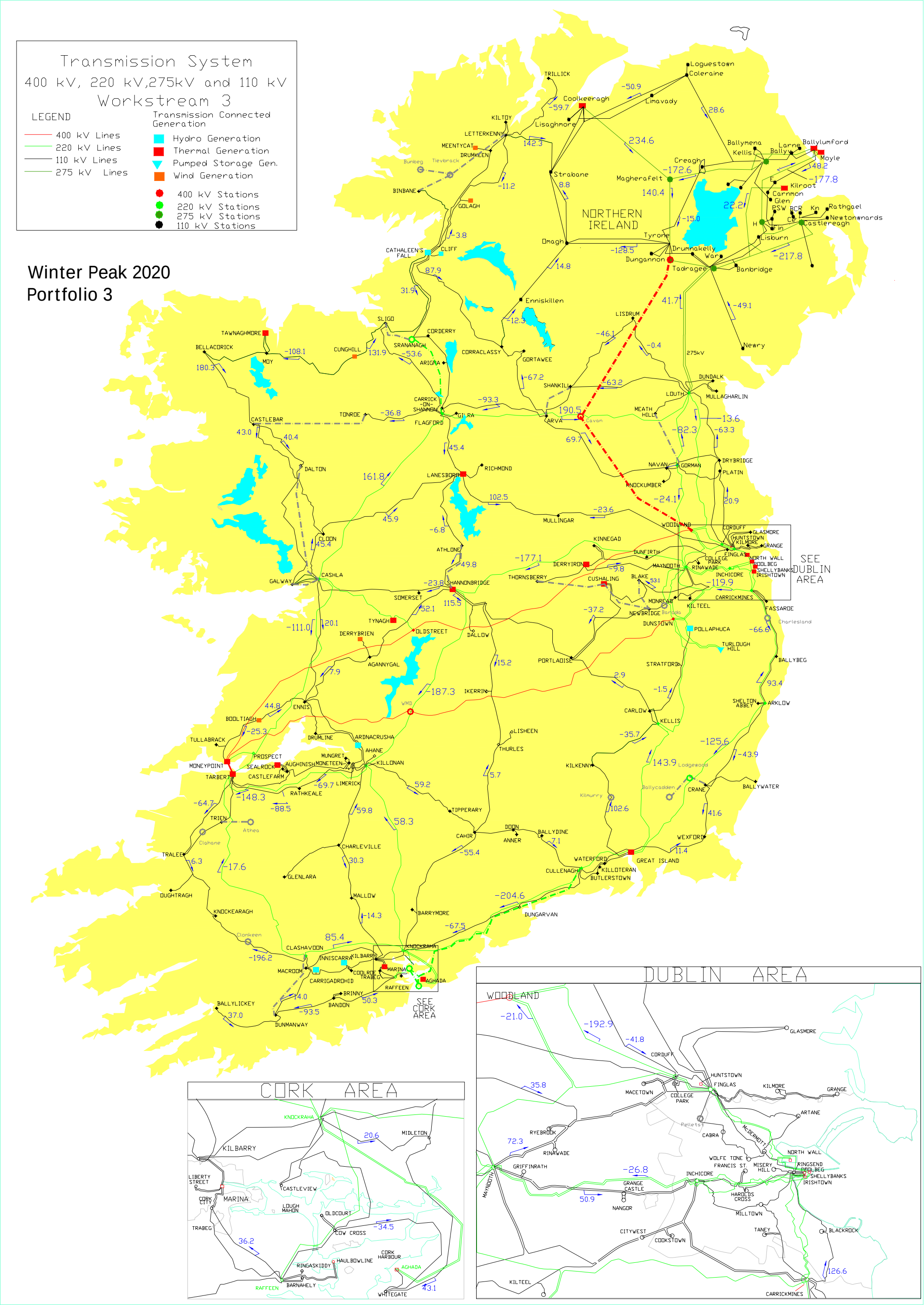


Figure C 3-Winter Peak – Intact System Flows – Portfolio 3

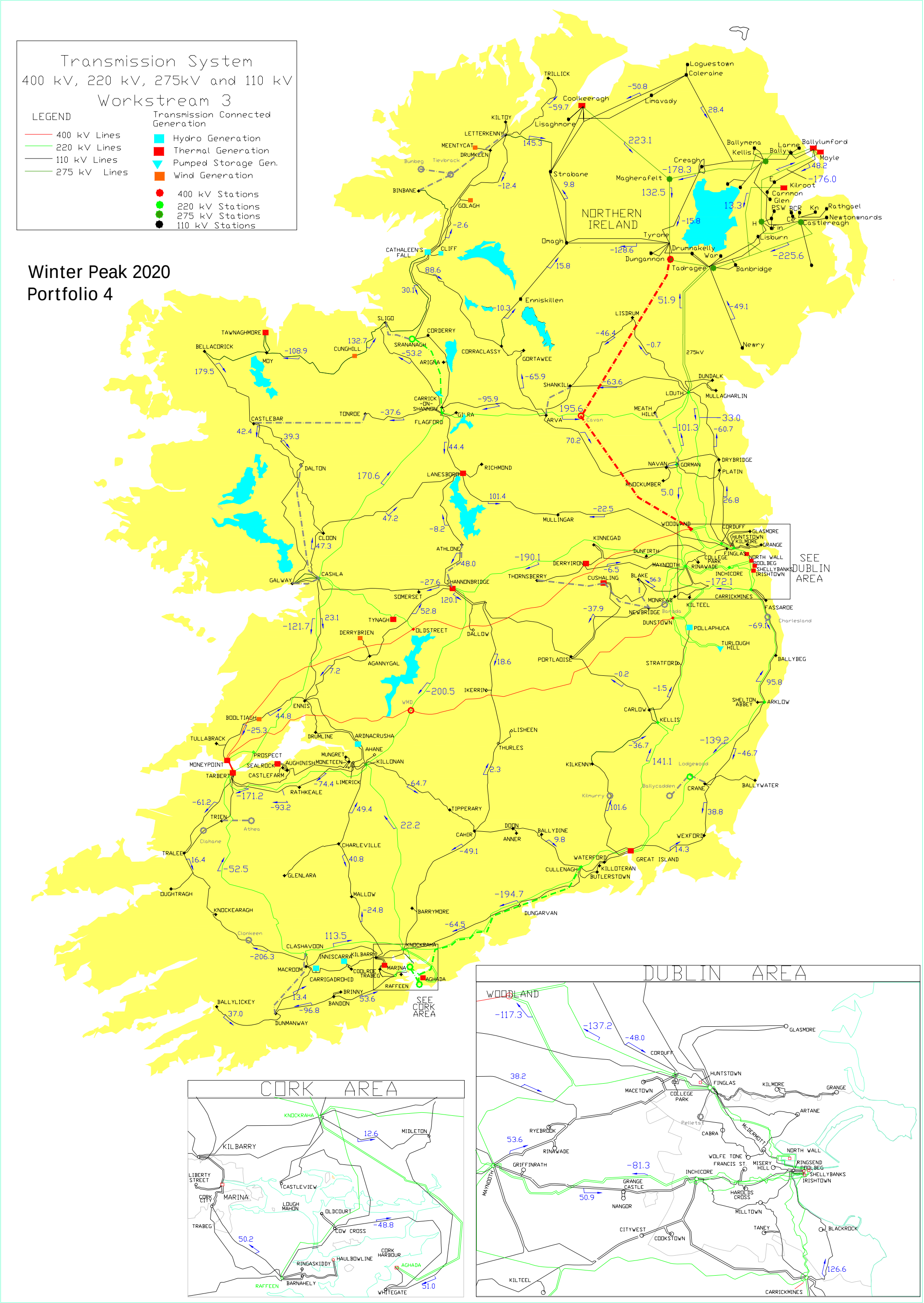
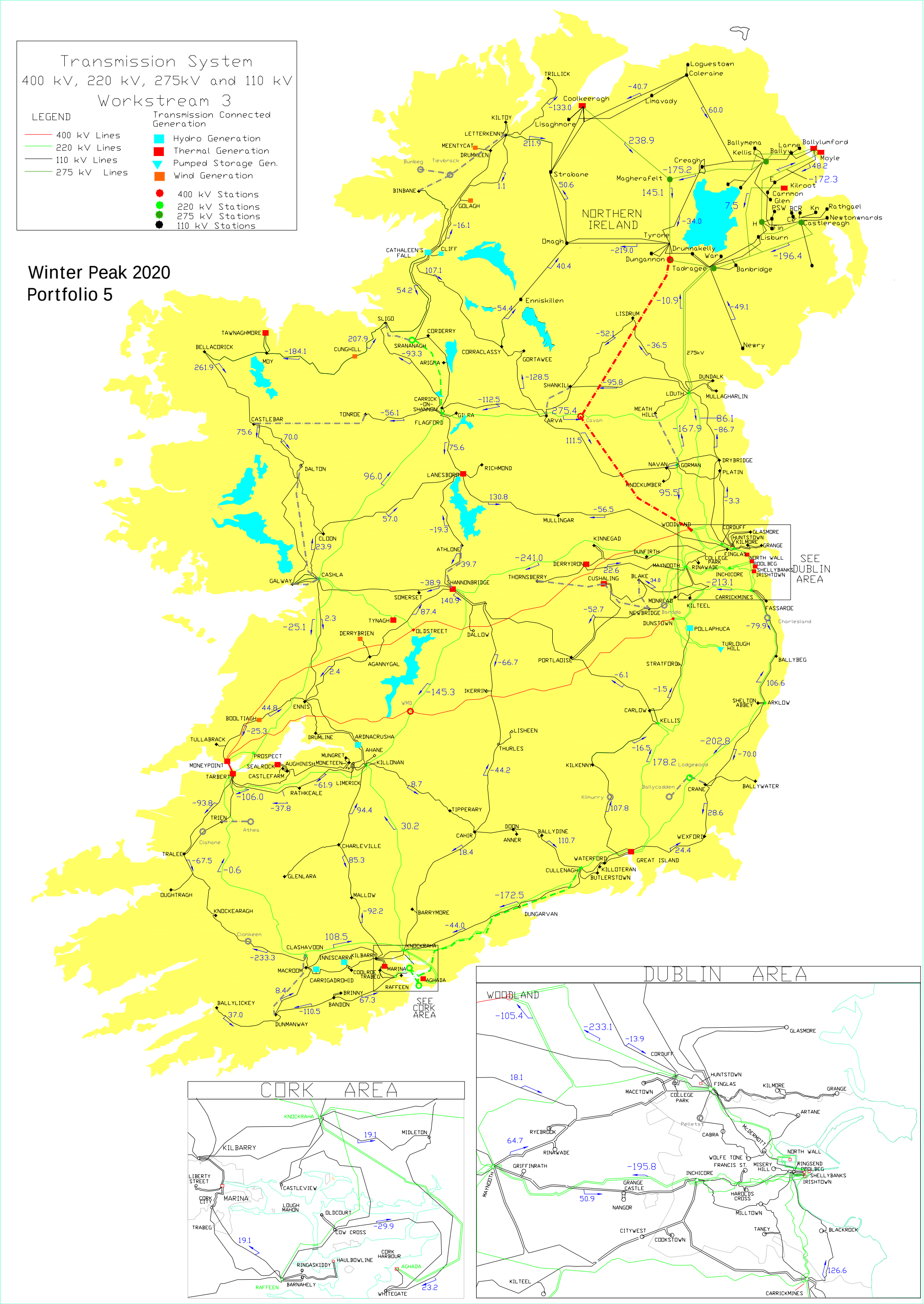


Figure C 4-Winter Peak – Intact System Flows – Portfolio 4



Winter Peak 2020
Portfolio 5

Figure C 5-Winter Peak – Intact System Flows – Portfolio 5

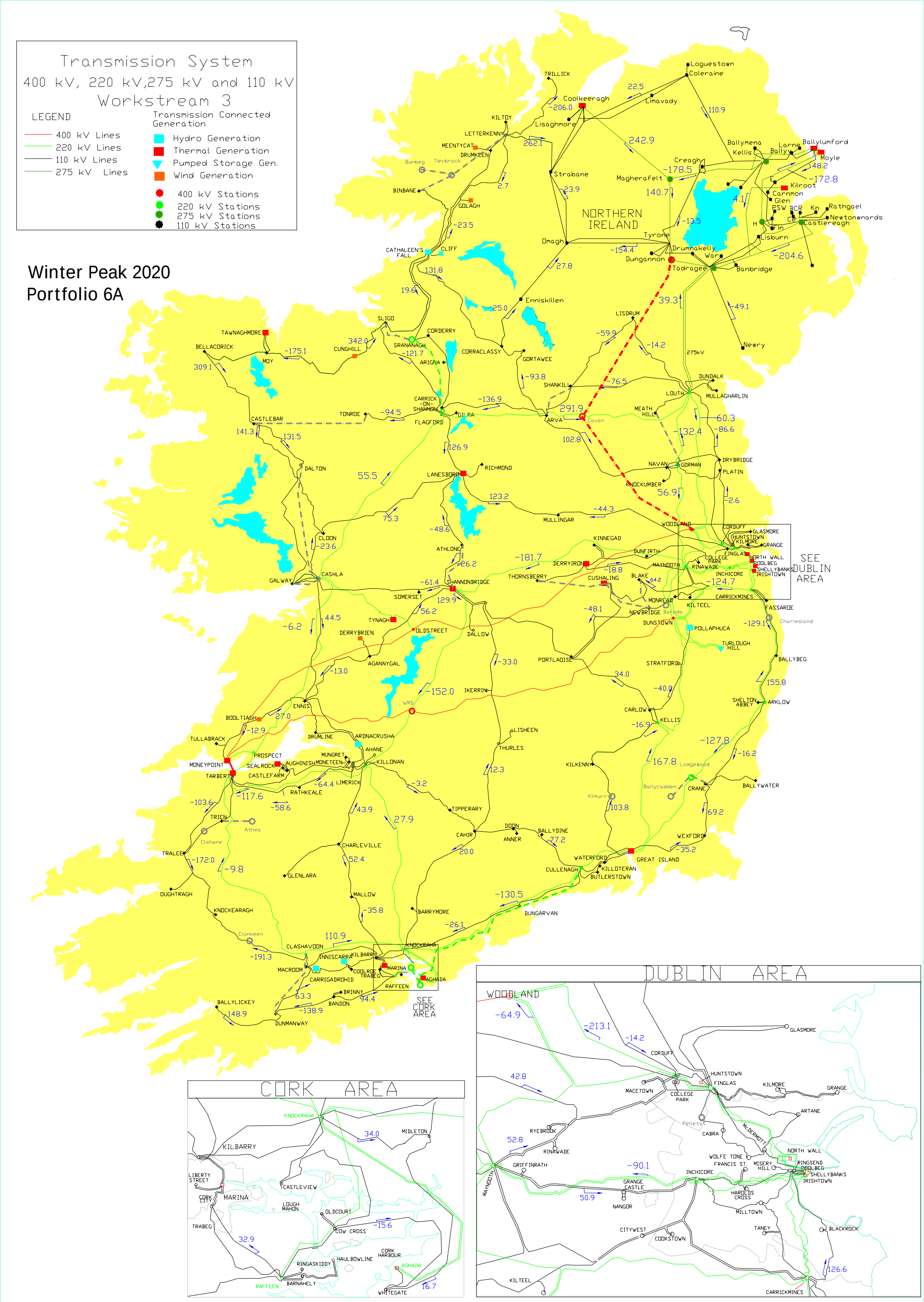


Figure C6-Winter Peak – Intact System Flows – Portfolio 6A

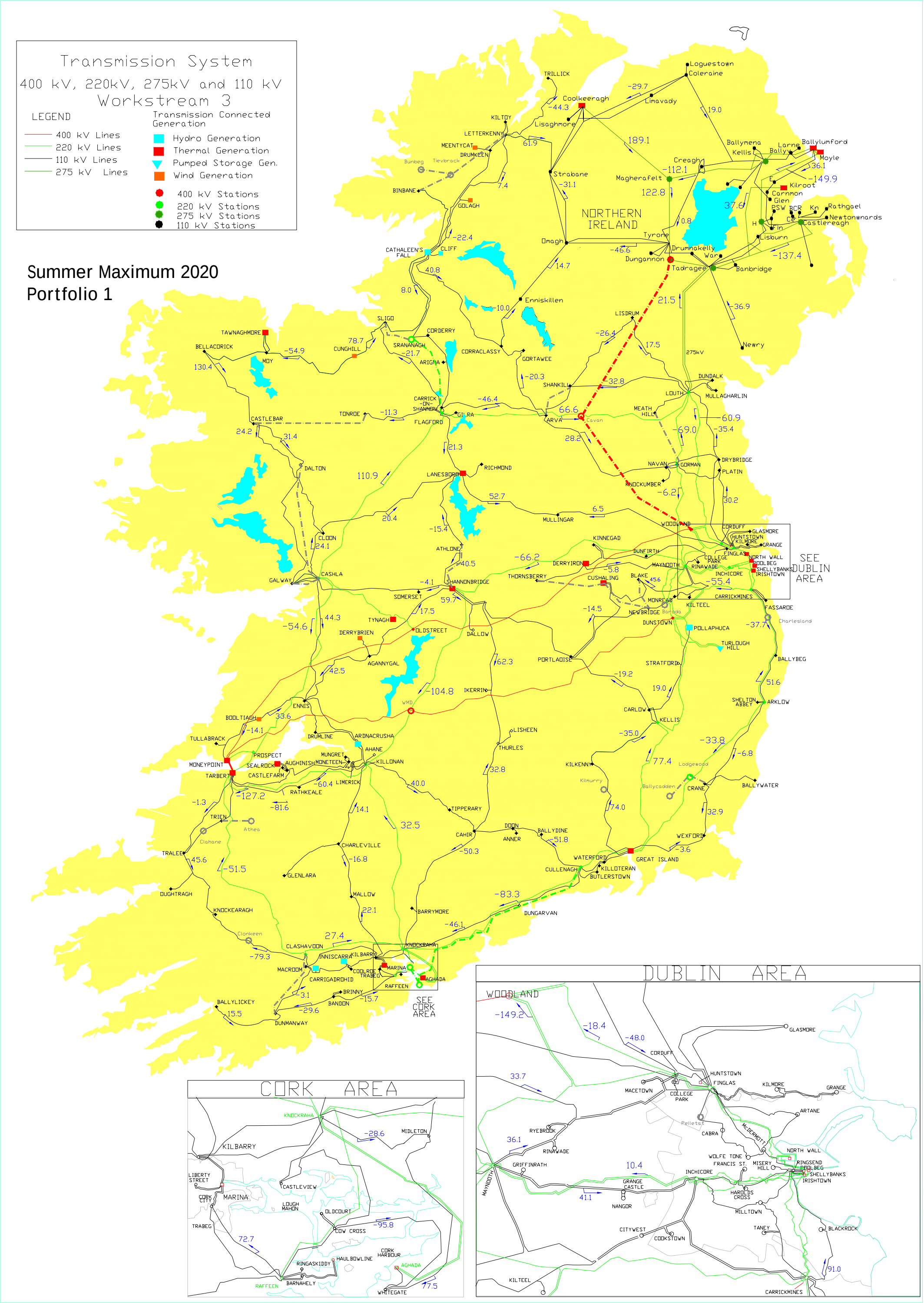


Figure C 7- Summer Maximum – Intact System Flows – Portfolio 1

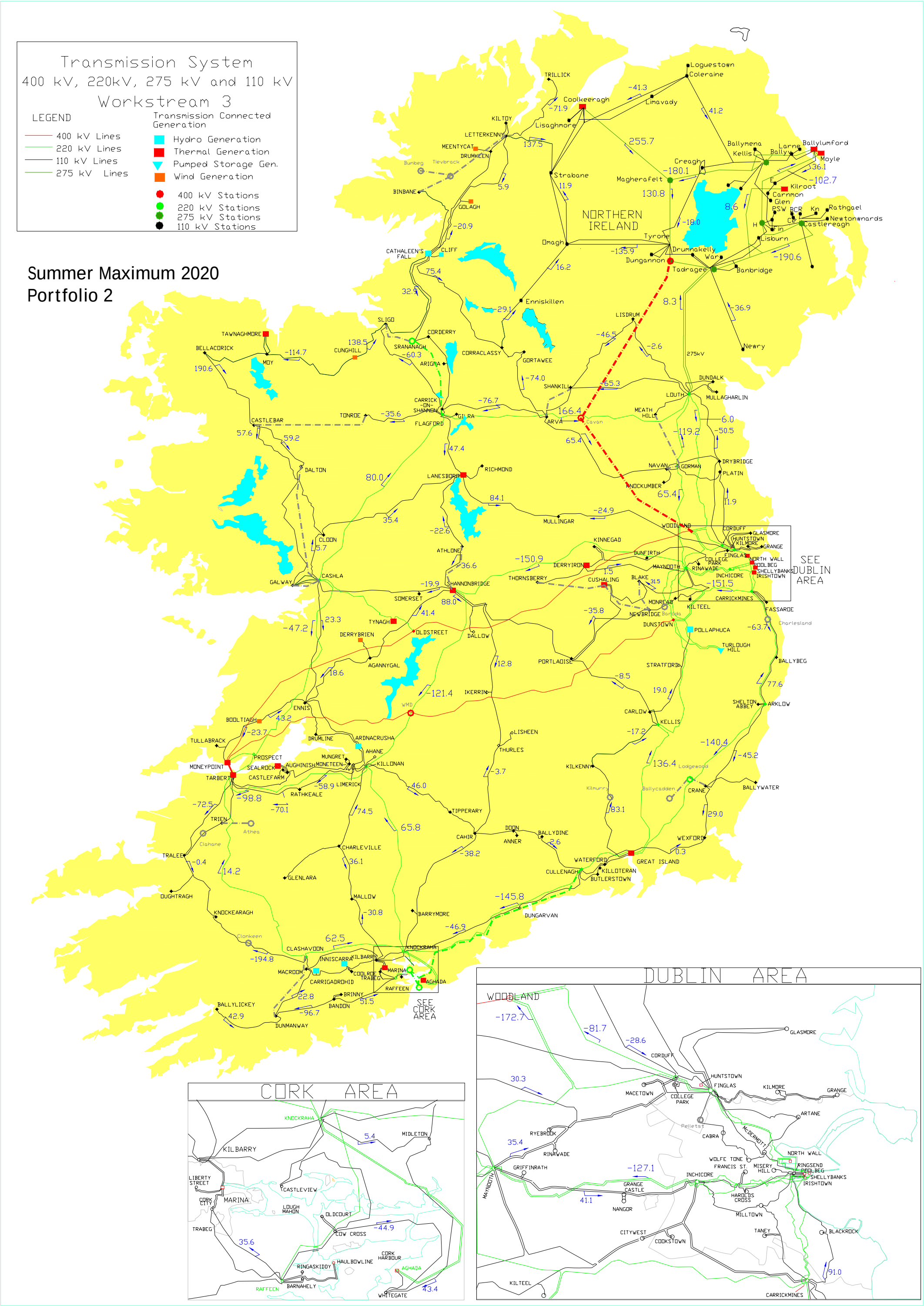


Figure C 8- Summer Maximum – Intact System Flows – Portfolio 2

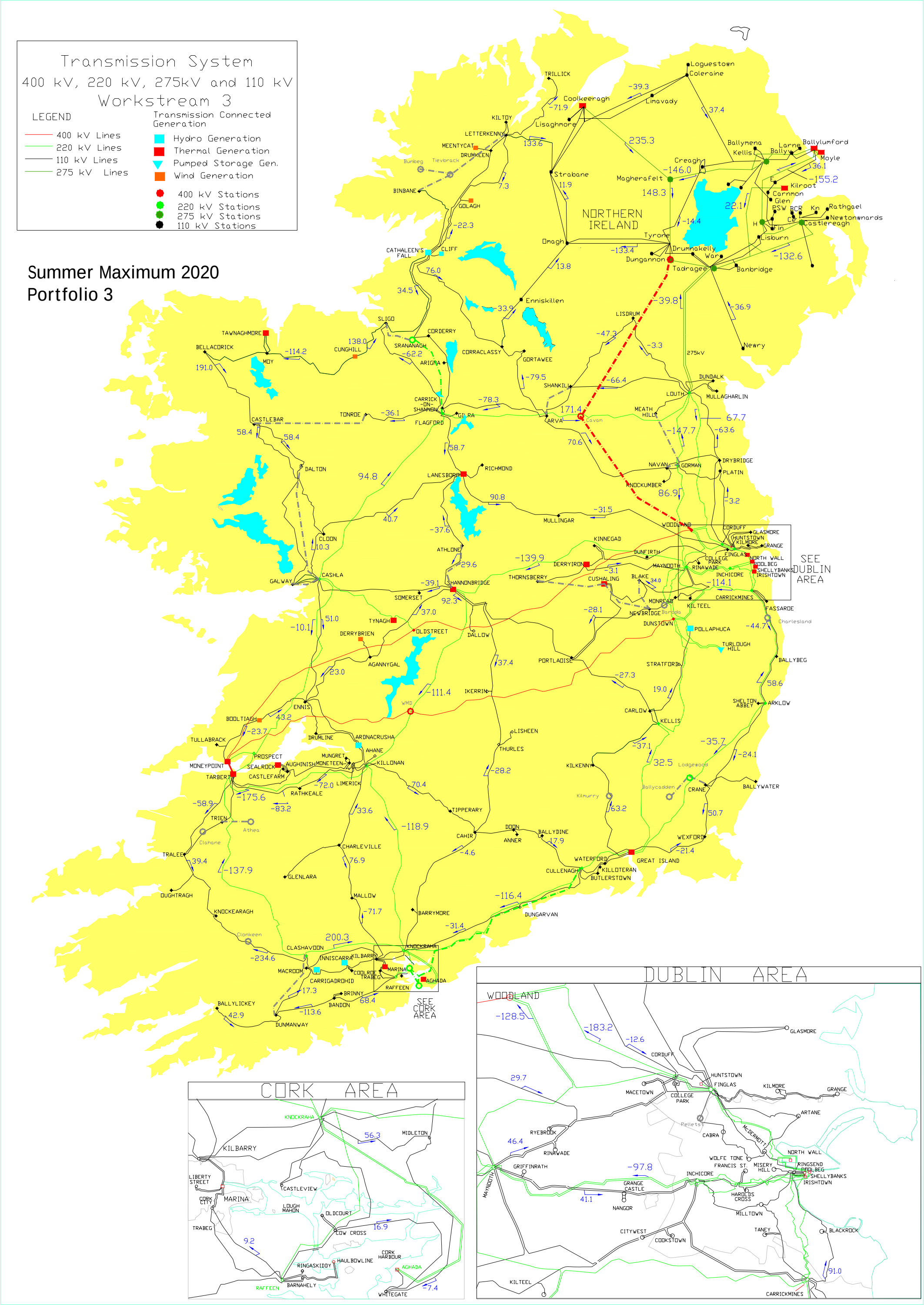


Figure C 9- Summer Maximum – Intact System Flows – Portfolio 3

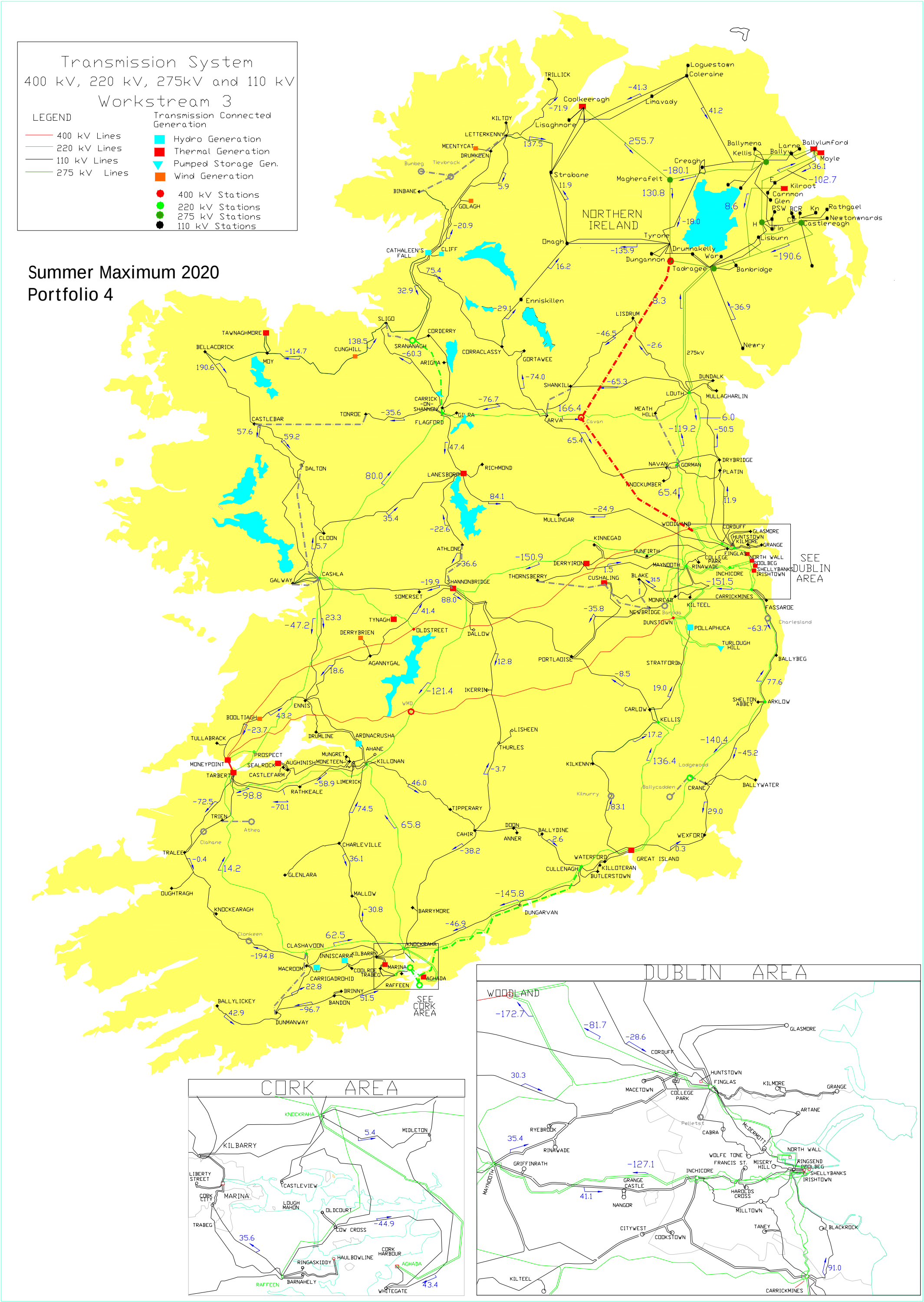
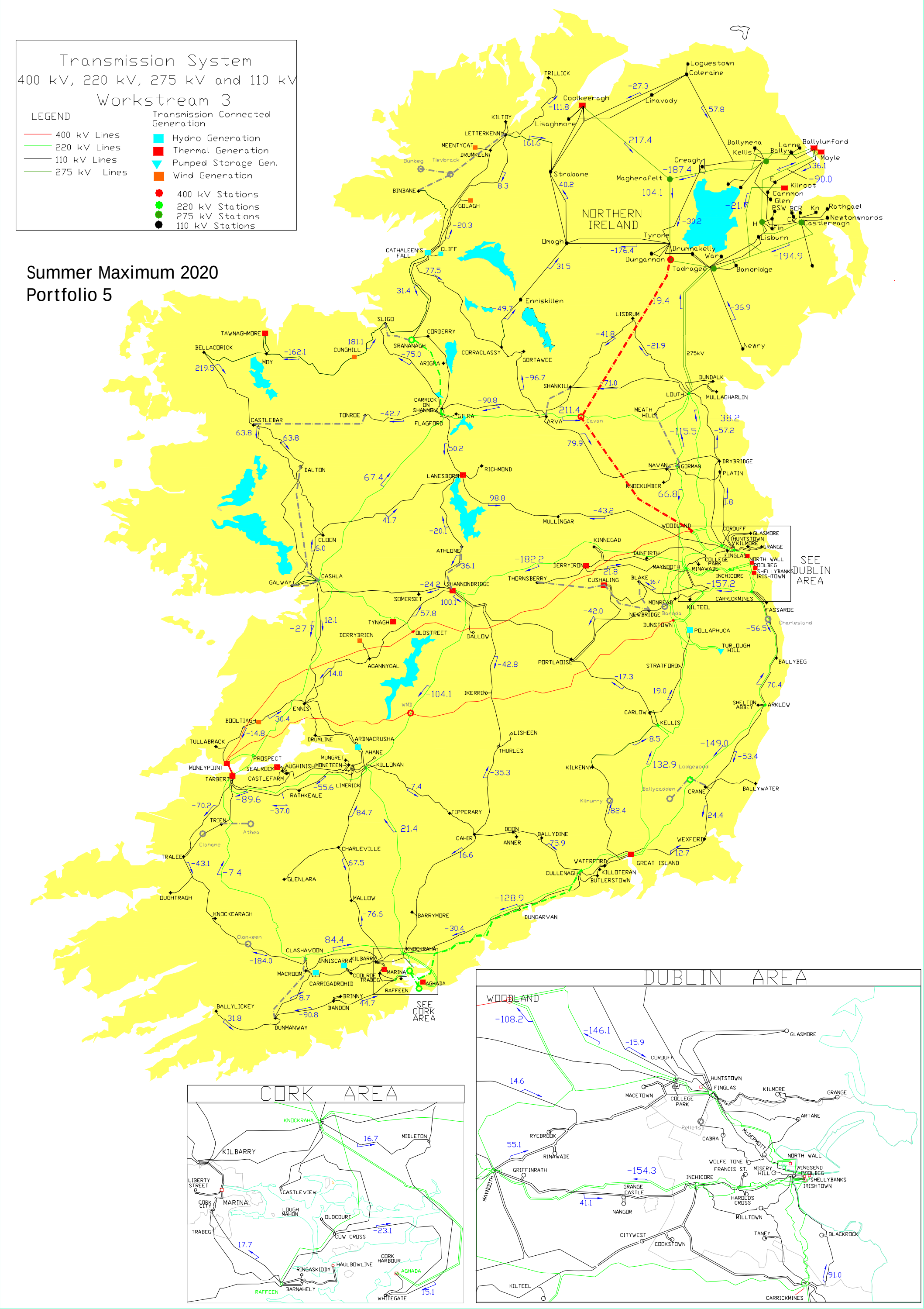
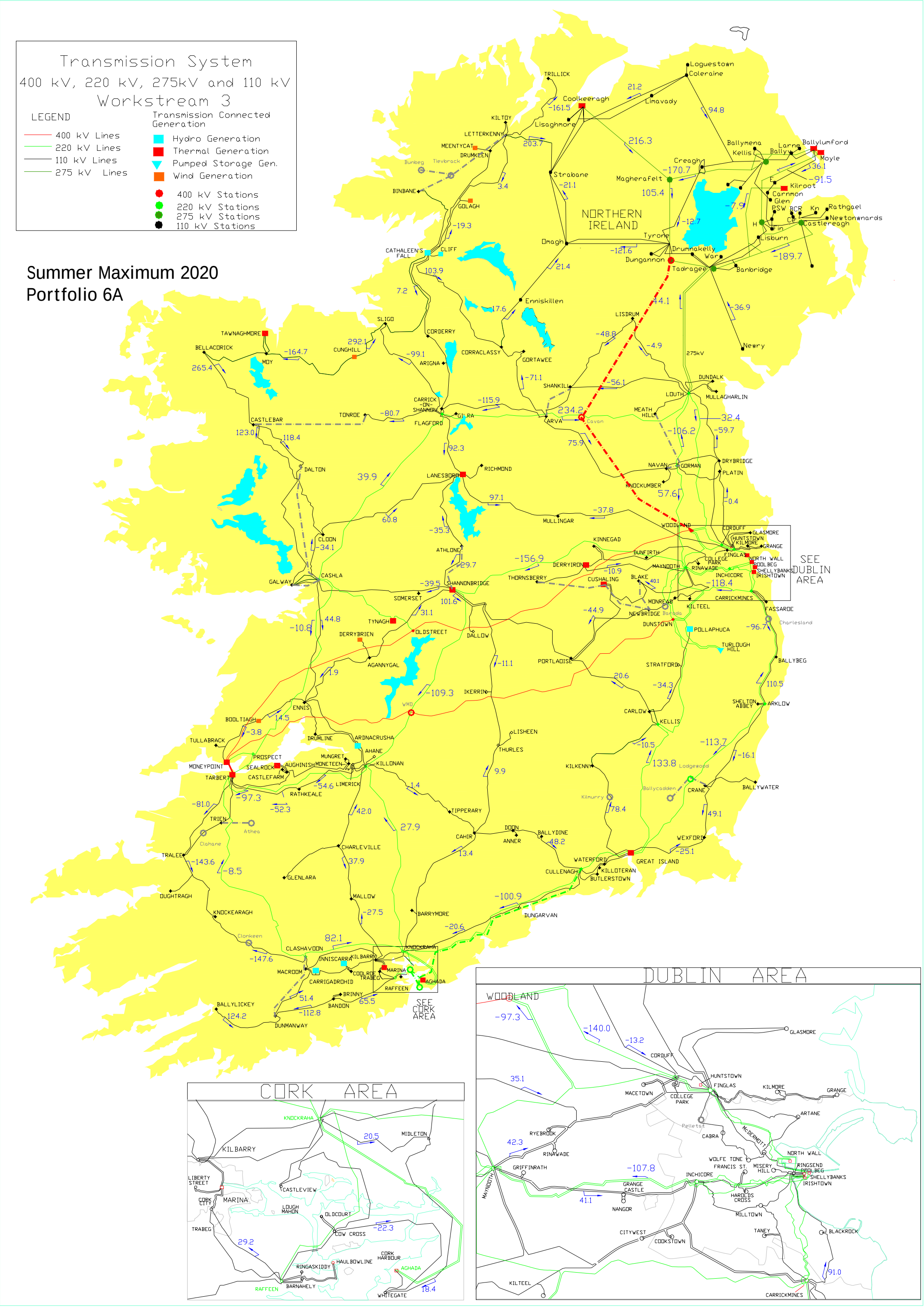


Figure C 10- Summer Maximum – Intact System Flows – Portfolio 4



Summer Maximum 2020
Portfolio 5

Figure C 11- Summer Maximum – Intact System Flows – Portfolio 5



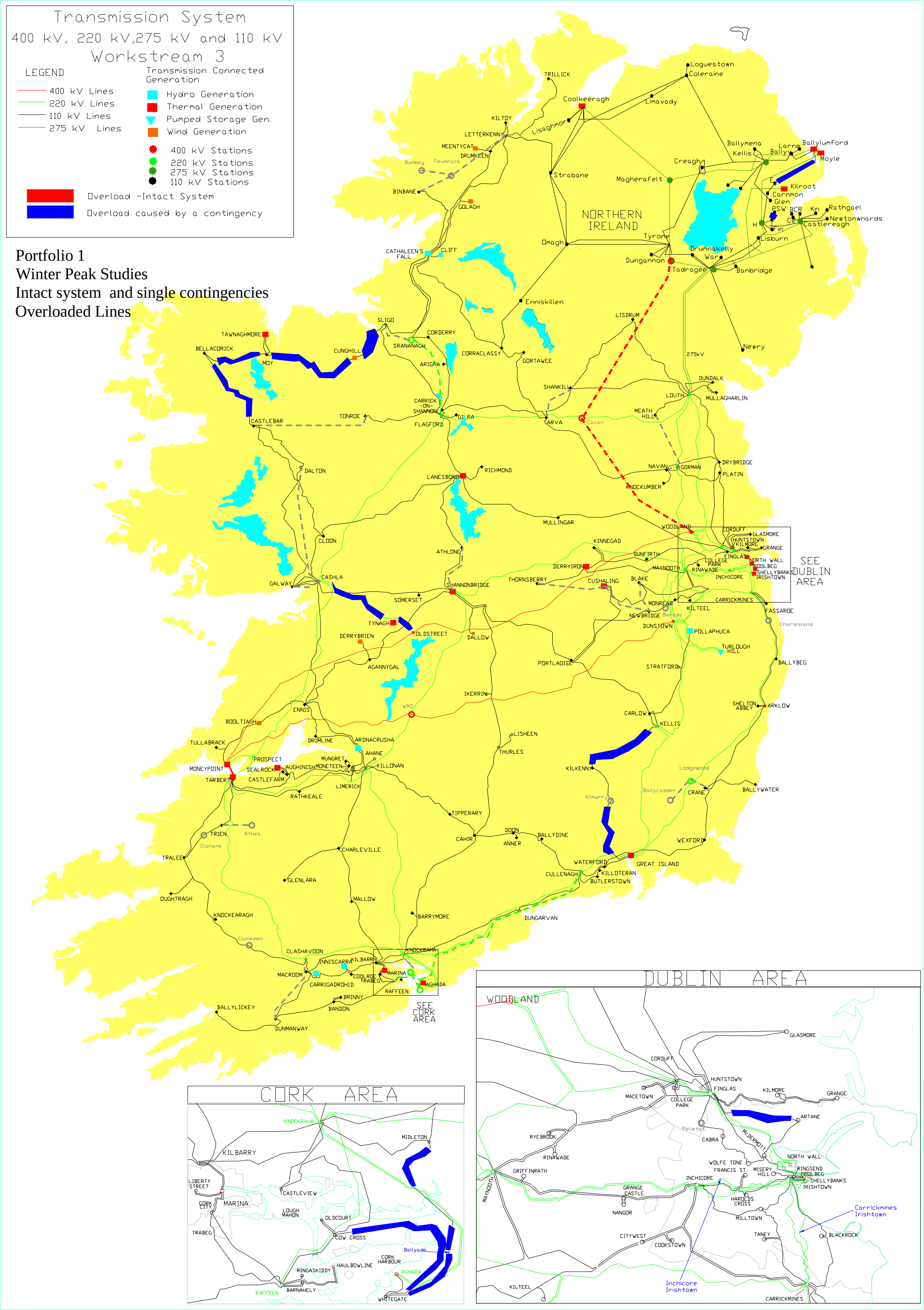
Summer Maximum 2020
Portfolio 6A

Figure C 12- Summer Maximum – Intact System Flows – Portfolio 6A

Appendix D

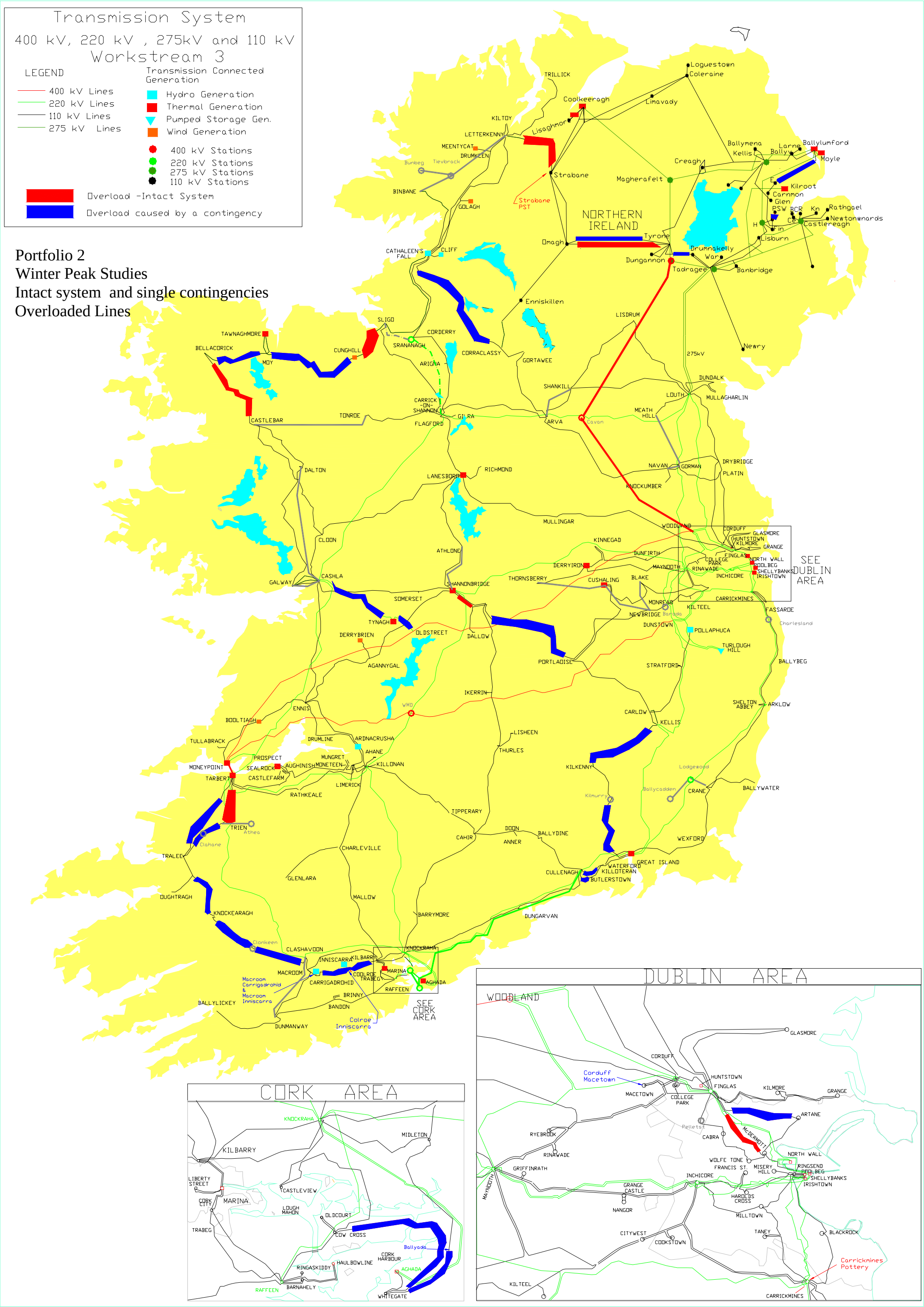
Disclaimer

The purpose of the network diagrams presented in the following appendices is only to illustrate the envisaged network reinforcements between 2007 and 2020, intact system network flows, the identified network overloads and the proposed network reinforcements. It should be pointed out that the network data used for the study were obtained directly from the TSOs and it might be some discrepancies between this data and the network diagrams herein.



Portfolio 1
Winter Peak Studies
Intact system and single contingencies
Overloaded Lines

Figure D1- Winter Peak - Overloaded lines - Portfolio 1



Portfolio 2
Winter Peak Studies
Intact system and single contingencies
Overloaded Lines

Figure D2- Winter Peak - Overloaded lines - Portfolio 2

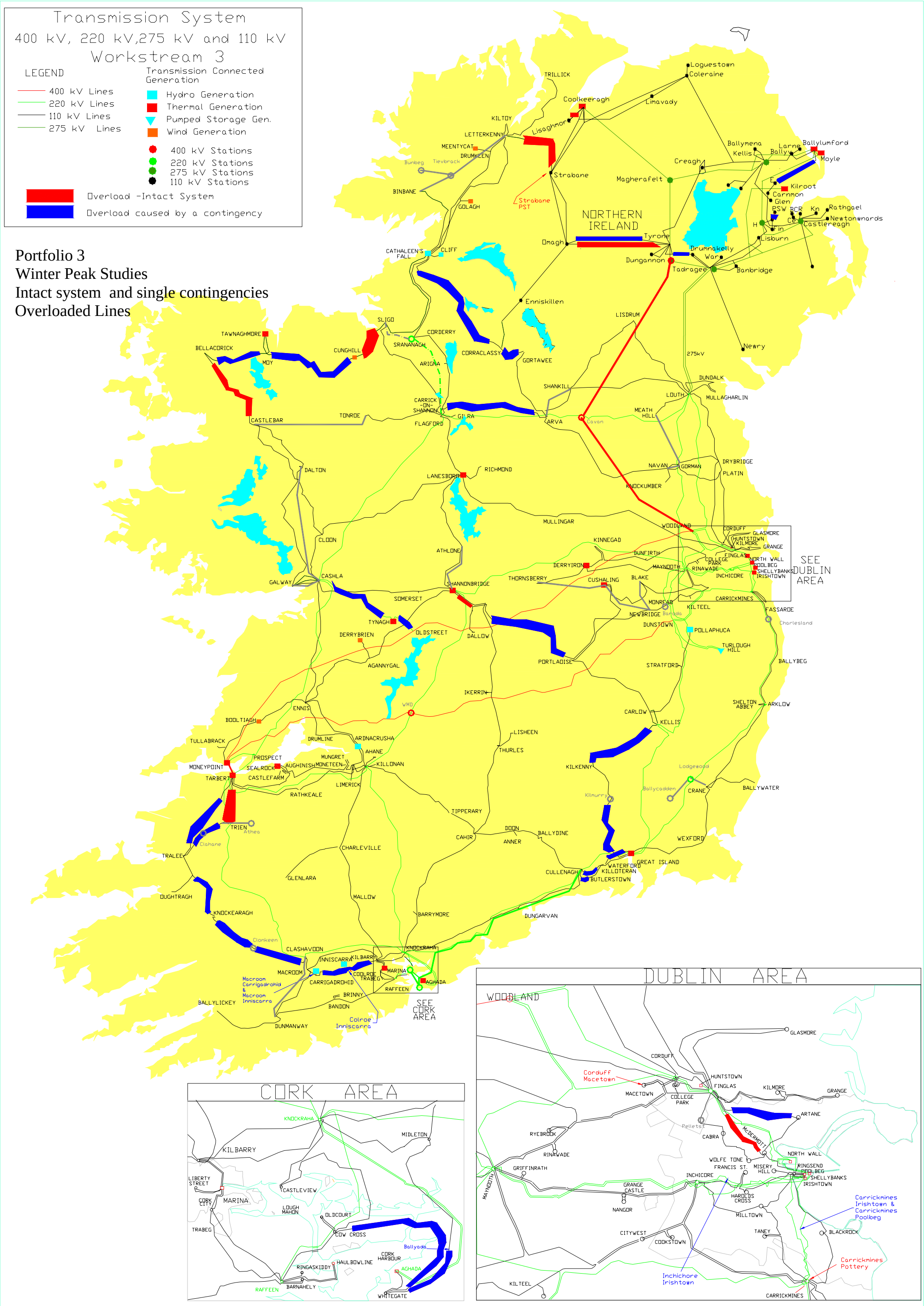
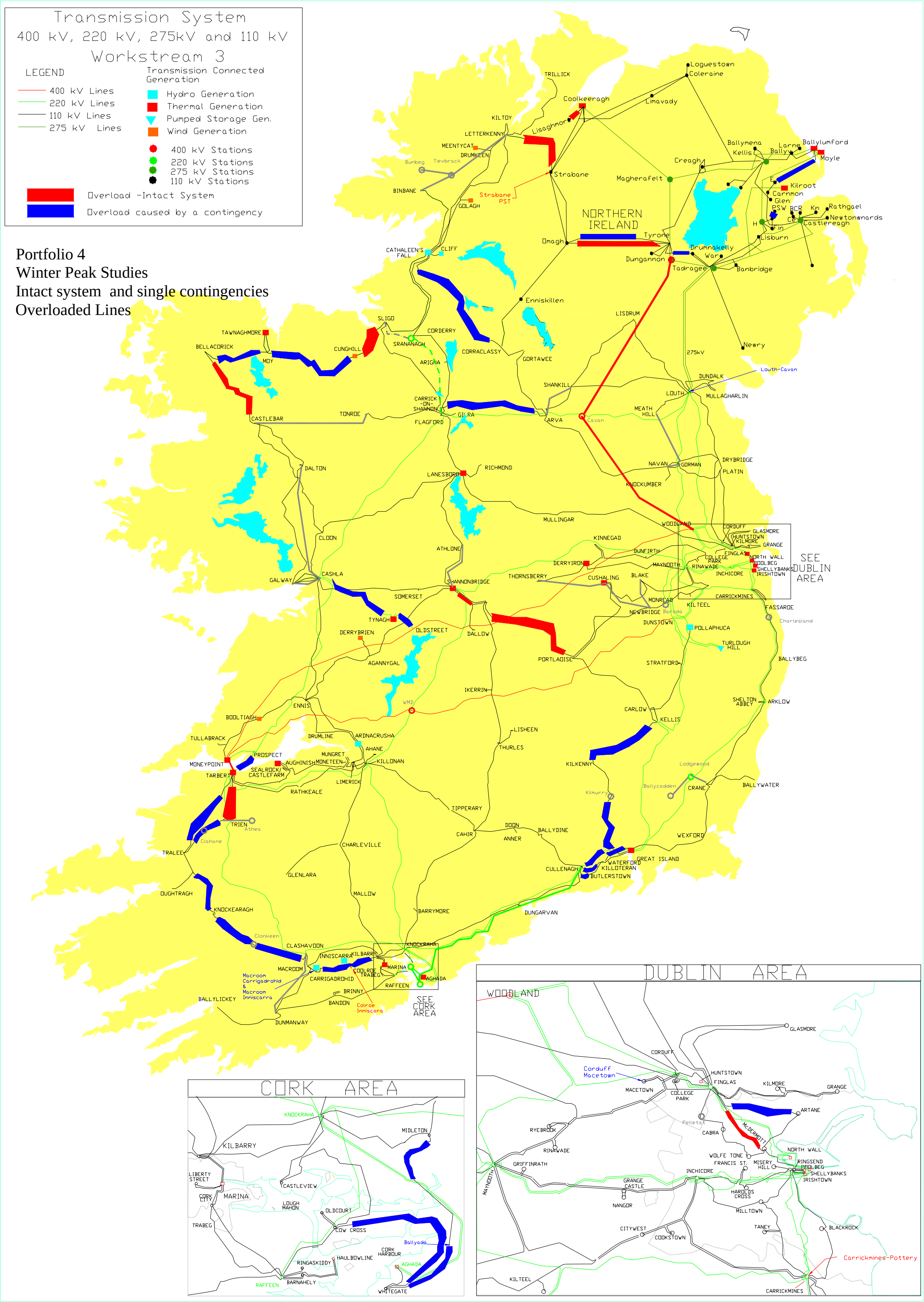
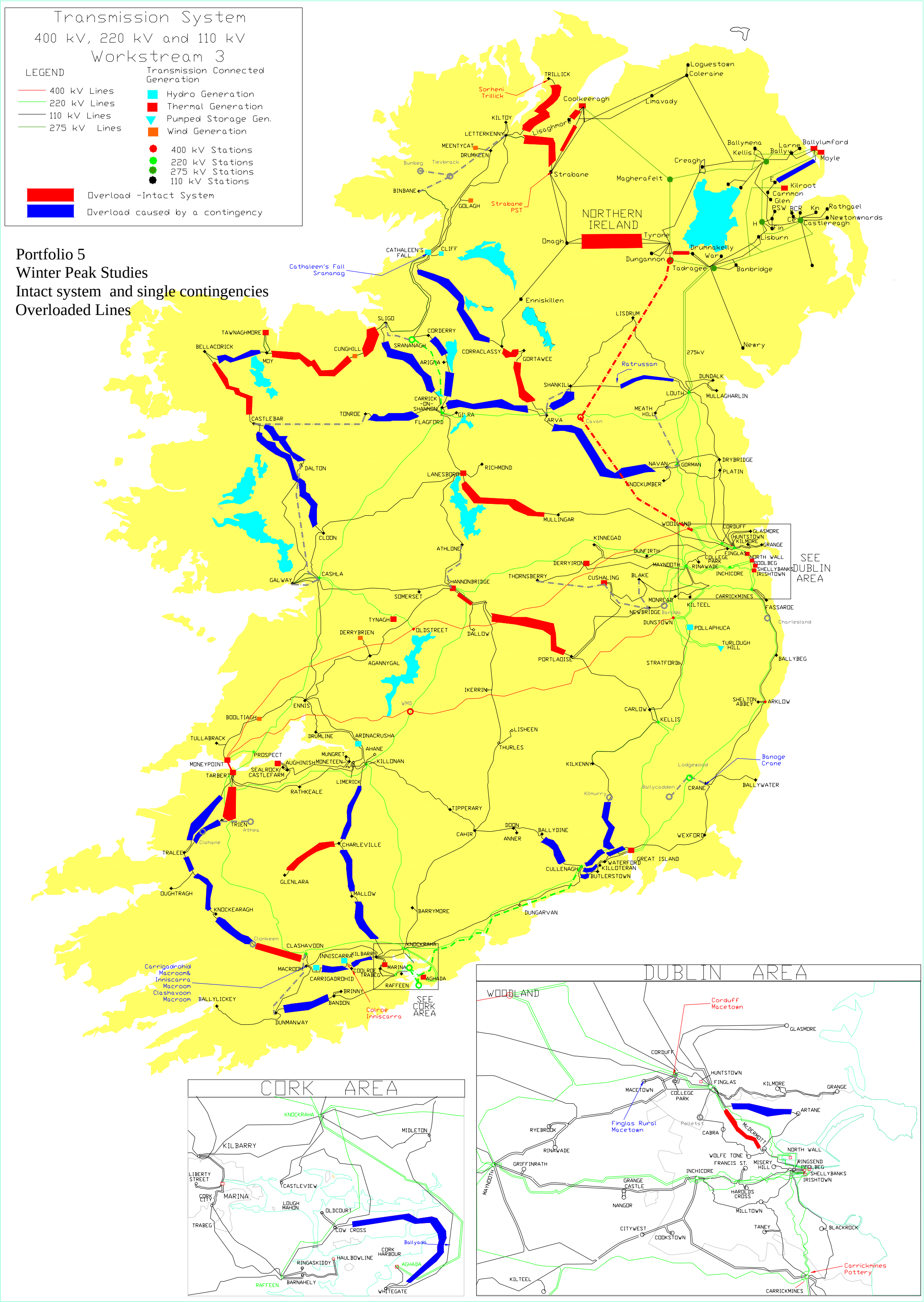


Figure D3- Winter Peak - Overloaded lines - Portfolio 3



Portfolio 4
Winter Peak Studies
Intact system and single contingencies
Overloaded Lines

Figure D4- Winter Peak - Overloaded lines - Portfolio 4



Portfolio 5
Winter Peak Studies
Intact system and single contingencies
Overloaded Lines

Figure D5- Winter Peak - Overloaded lines - Portfolio 5

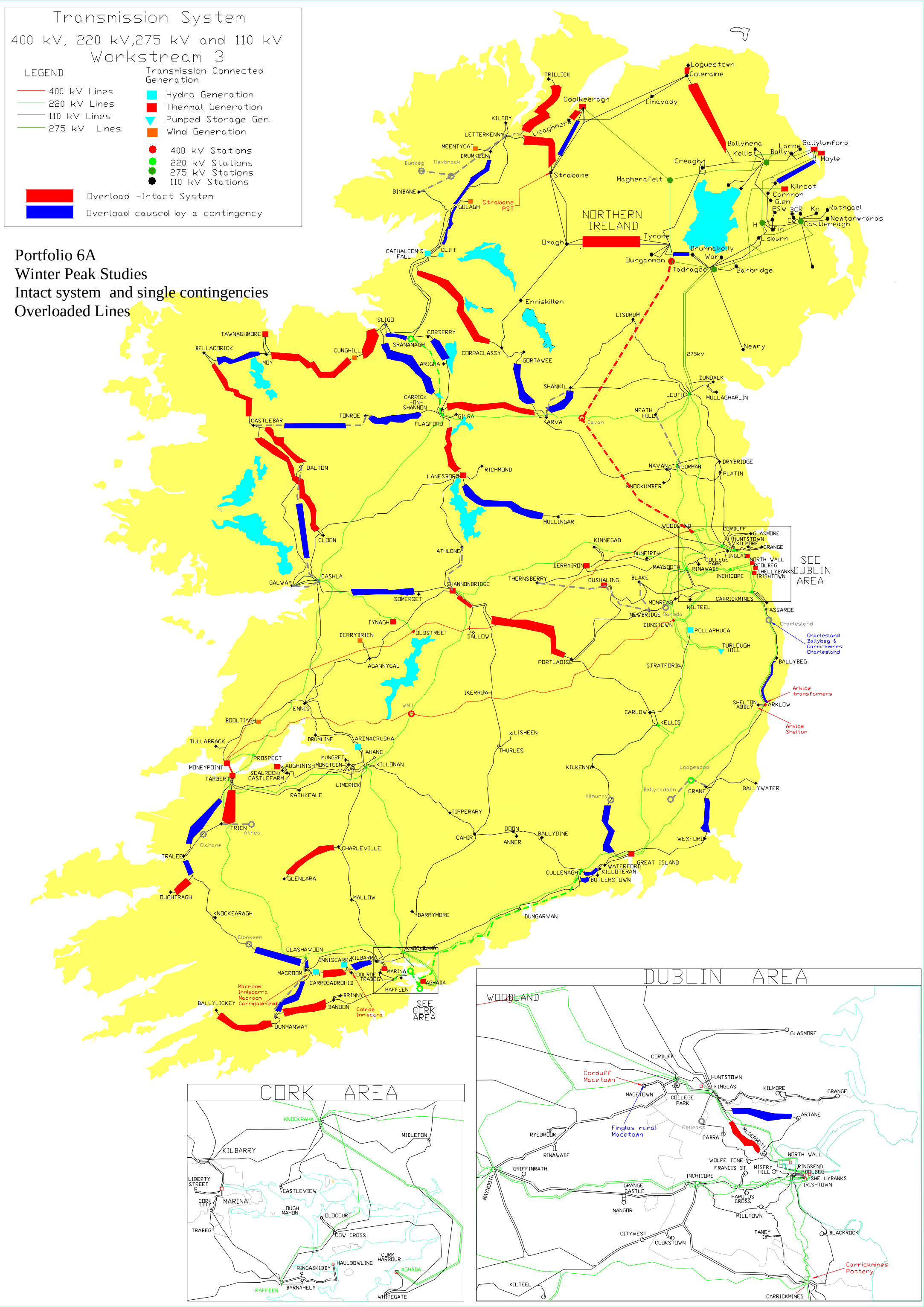


Figure D6-Winter Peak - Overloaded lines - Portfolio 6A

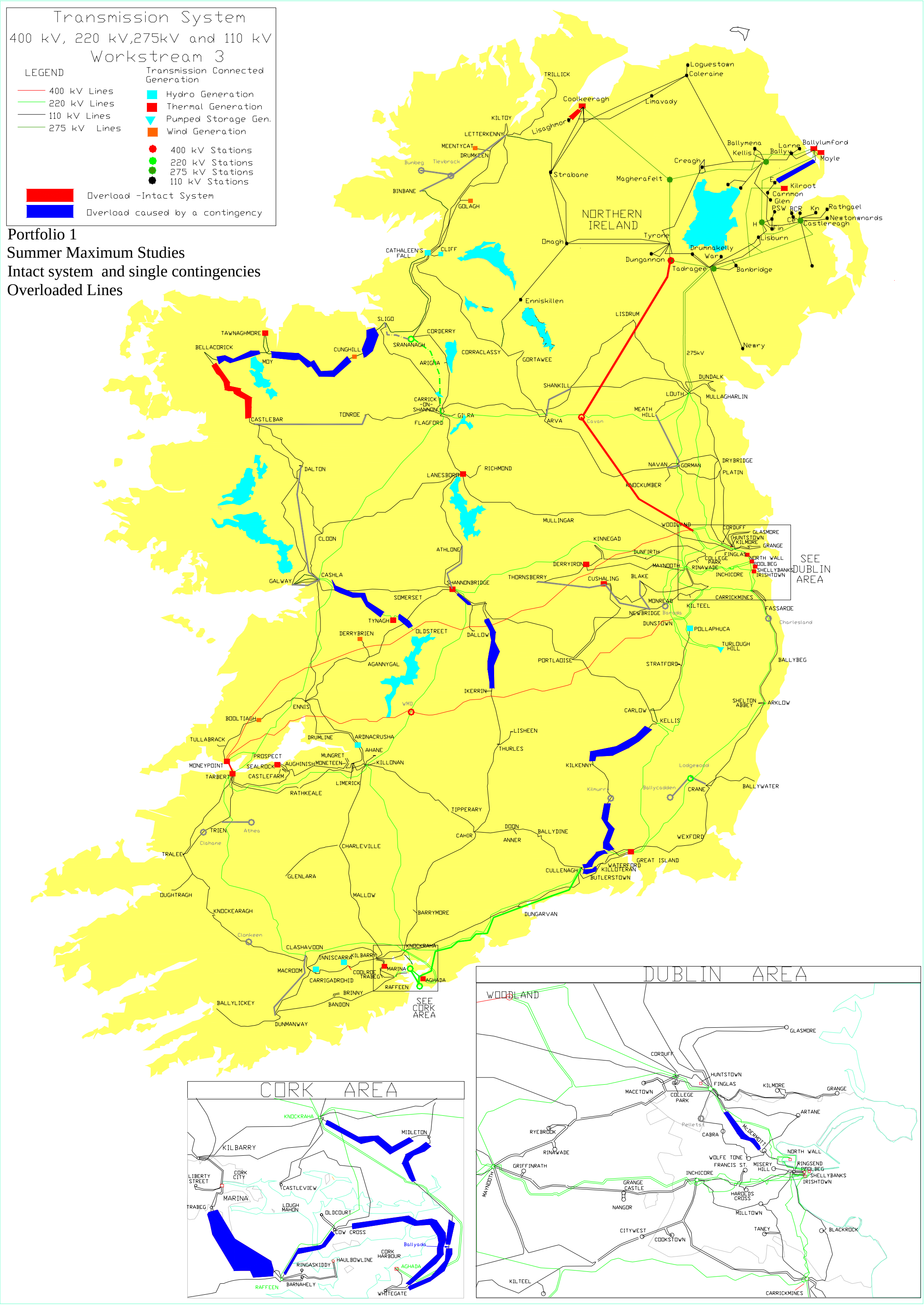
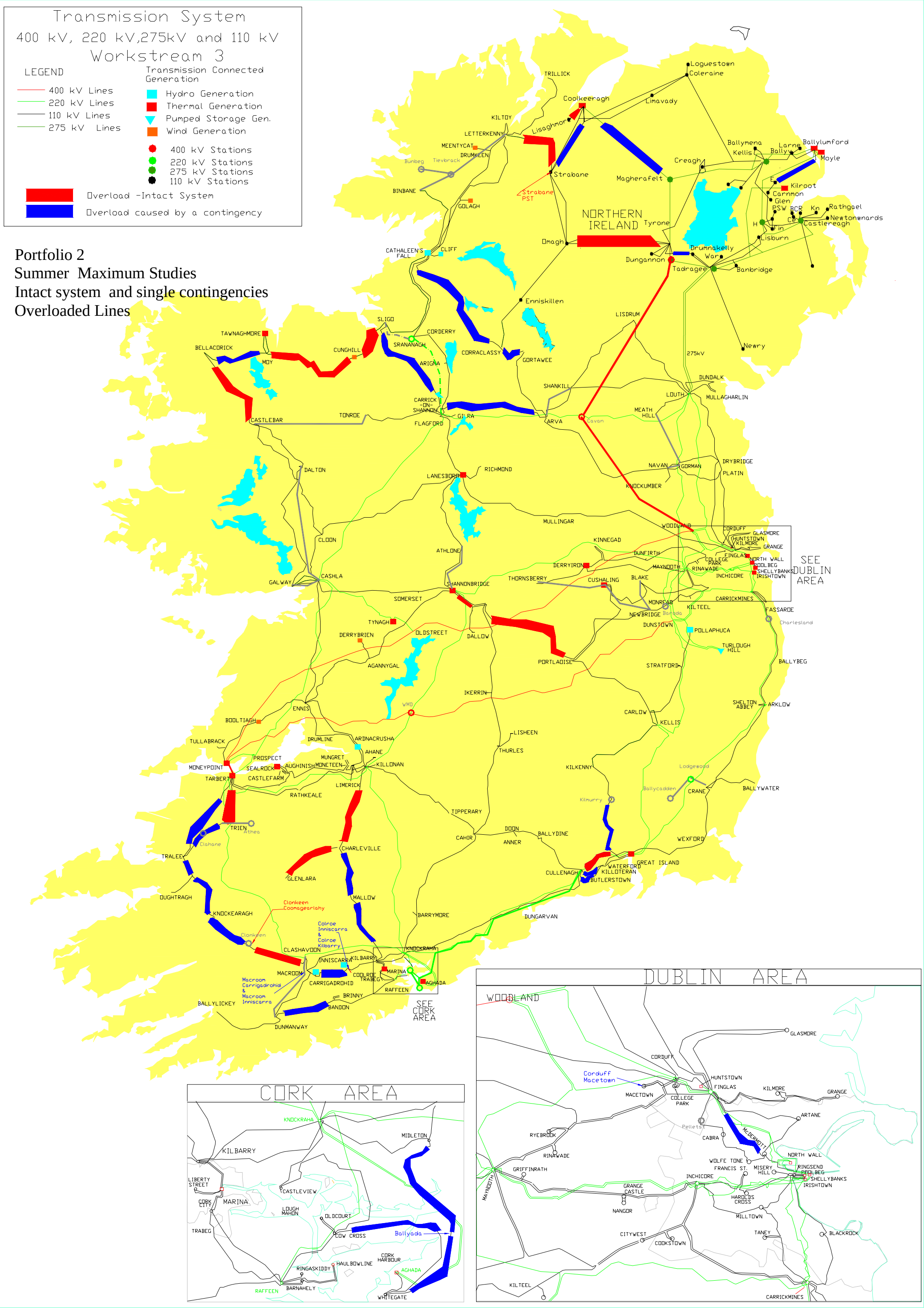
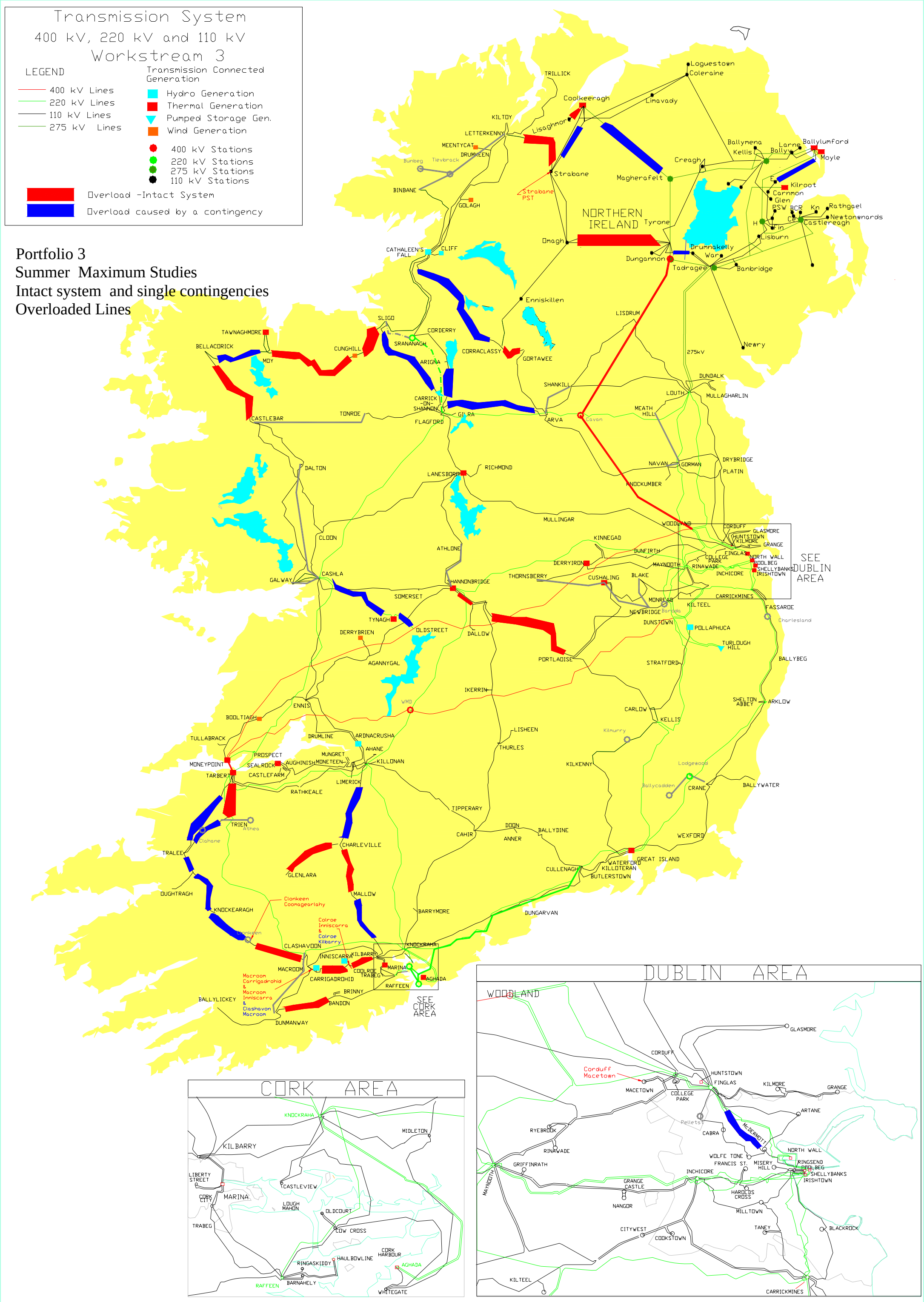


Figure D7– Summer Maximum - Overloaded lines - Portfolio 1



Portfolio 2
Summer Maximum Studies
Intact system and single contingencies
Overloaded Lines

Figure D8– Summer Maximum - Overloaded lines - Portfolio 2



Portfolio 3
Summer Maximum Studies
Intact system and single contingencies
Overloaded Lines

Figure D9- Summer Maximum - Overloaded lines - Portfolio 3

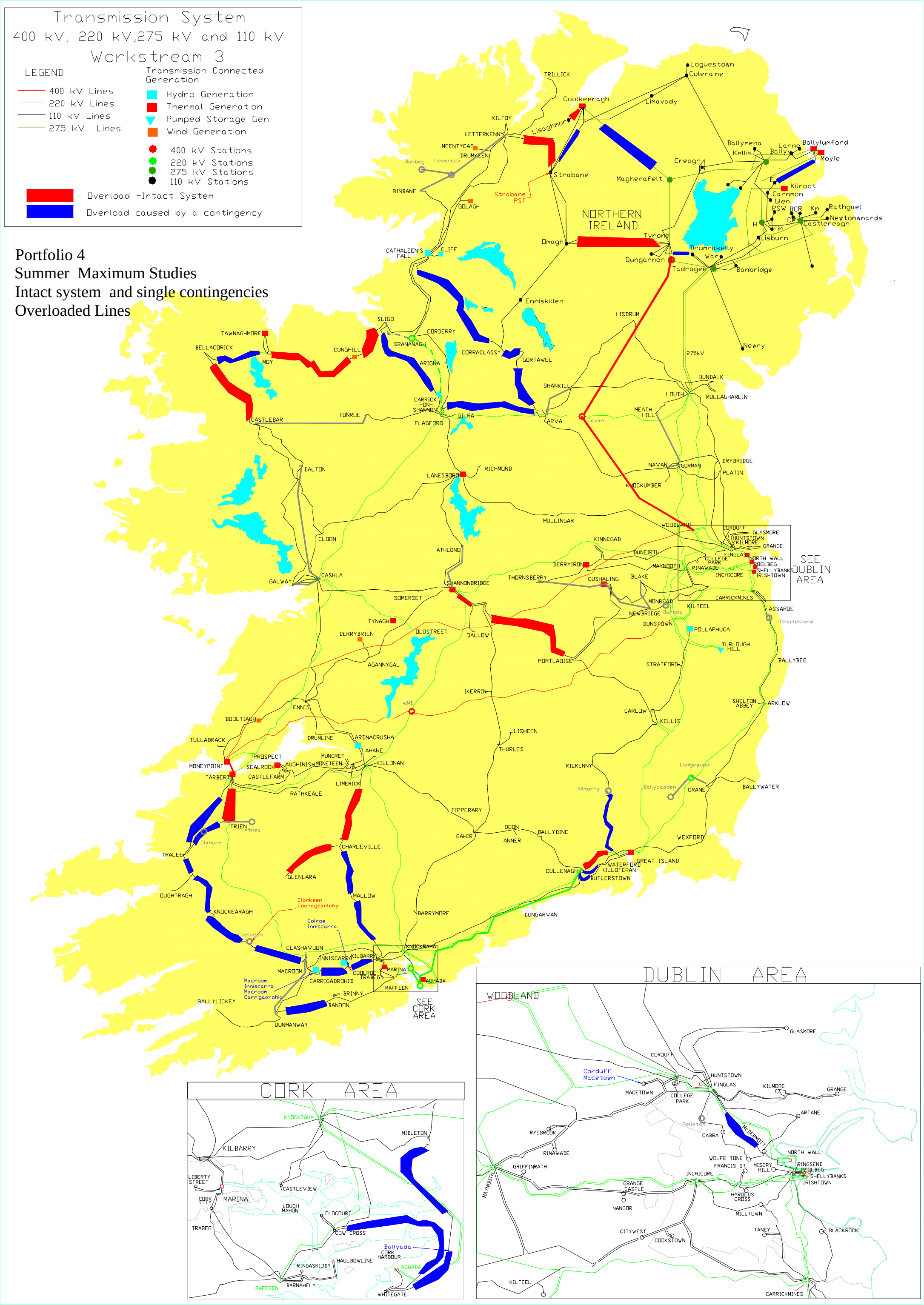


Figure D10-Summer Maximum - Overloaded lines - Portfolio 4

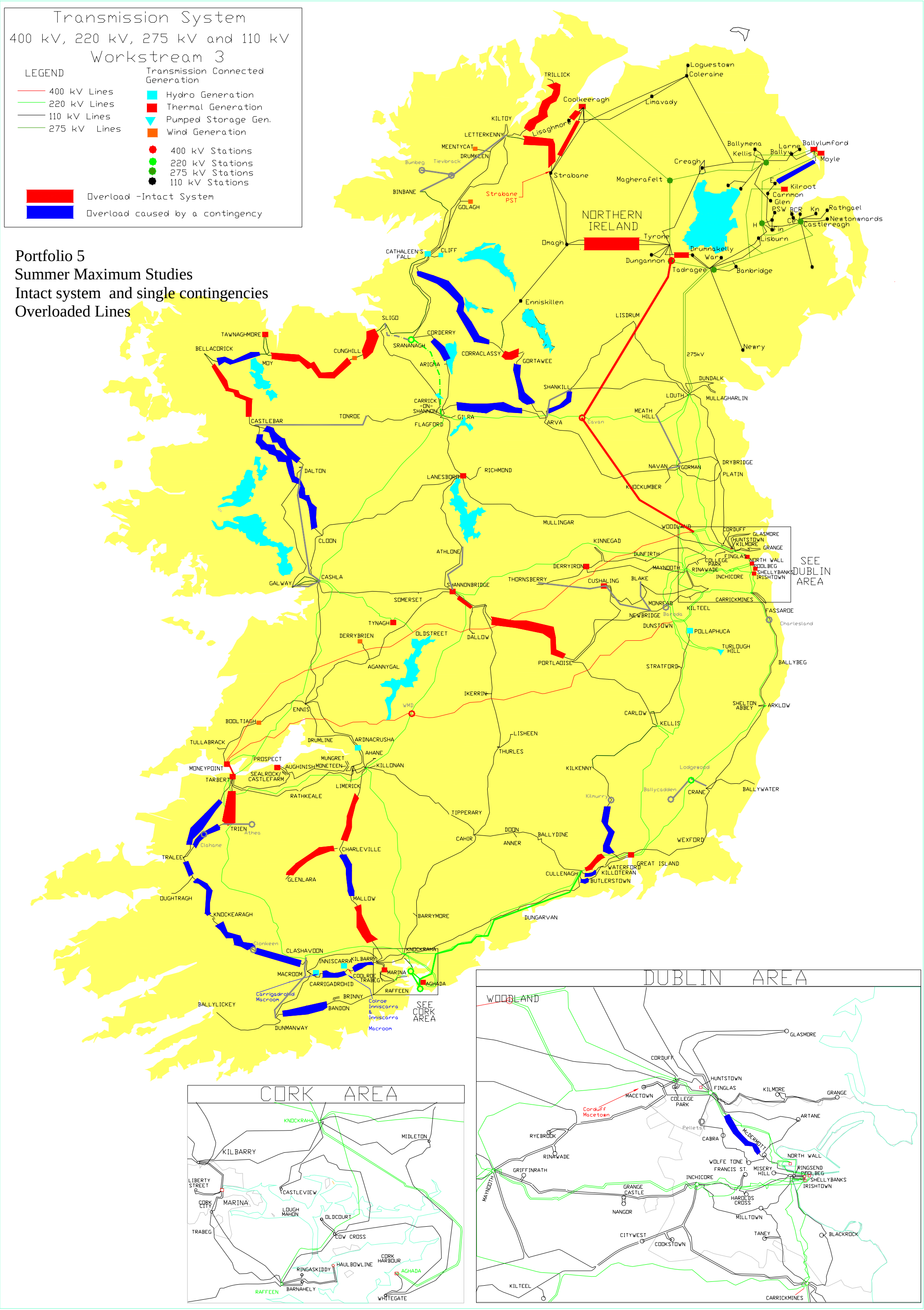


Figure D11-Summer Maximum - Overloaded lines - Portfolio 5

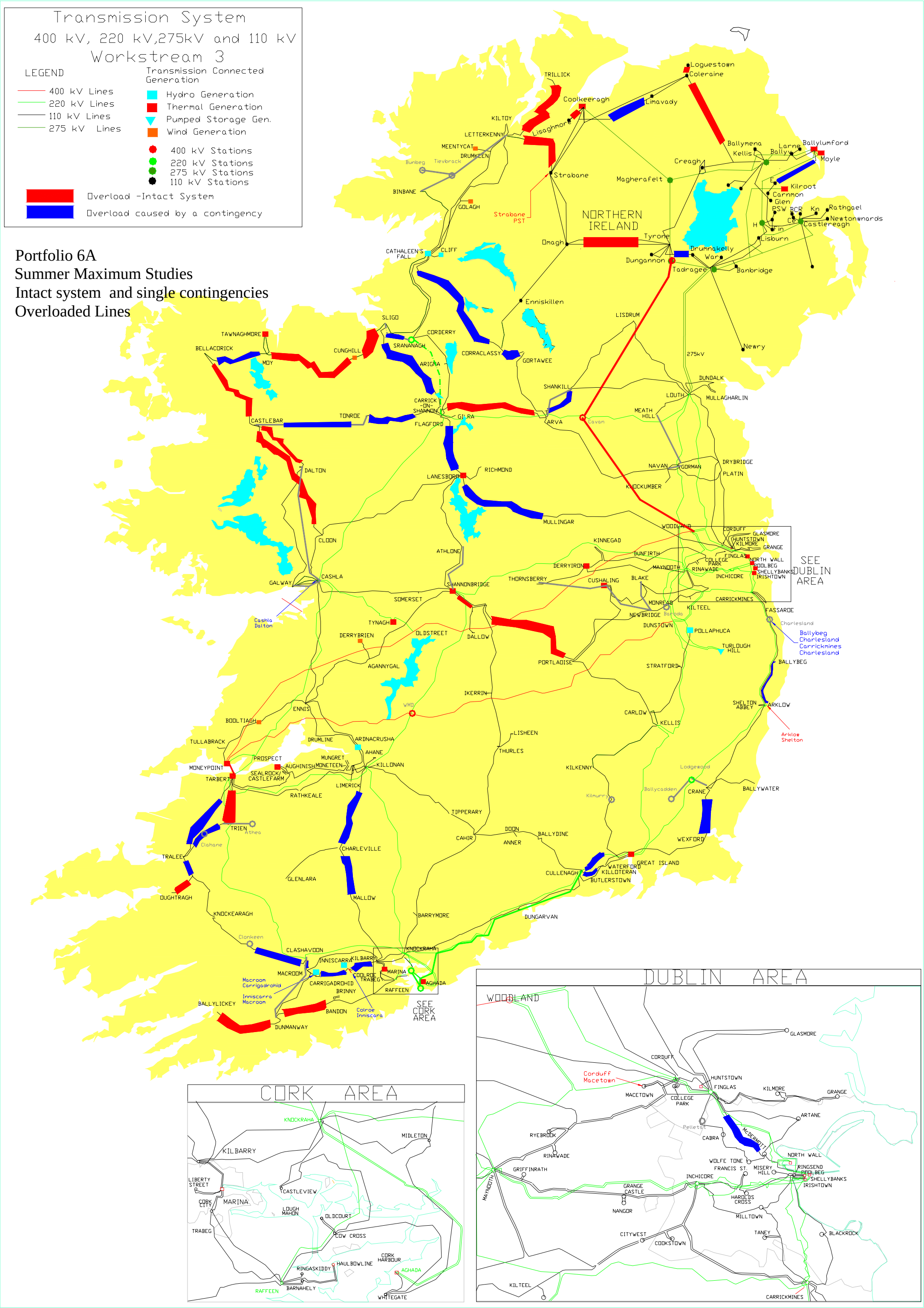


Figure D12-Summer Maximum - Overloaded lines - Portfolio 6A

Appendix E

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Winter Peak – Portfolio 1

Table E 1-Most frequently overloaded lines – Winter Peak -Portfolio 1

Overloaded lines					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of trials >>**[27]	**Number of trials >**[27]
1401	BELLACORICK	1661	CASTLEBAR	479	2664
1401	BELLACORICK	4041	MOY	479	2664
1931	CUNGHILL	4981	SLIGO	106	2229

Table E 2– Lines that frequently cause overloads – Winter Peak –Portfolio 1

Lines whose outage causes overloads					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of caused overloads >>**	**Number of caused overloads >**
1401	BELLACORICK	1661	CASTLEBAR	585	6451
1401	BELLACORICK	4041	MOY	479	2664

Winter Peak – Portfolio 2

Table E 3-Most frequently overloaded lines – Winter Peak-Portfolio 2

Overloaded lines					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of trials>>**	**Number of trials>**
1401	BELLACORICK	1661	CASTLEBAR	3197	1487
1931	CUNGHILL	4981	SLIGO	3197	1487
1931	CUNGHILL	4041	MOY	2766	1562
1651	CLAHANE	5281	TRALEE	2638	1763
5141	TARBERT	5261	TRIEN	2550	1832
1651	CLAHANE	5261	TRIEN	1707	1934
1401	BELLACORICK	4041	MOY	1188	2421
89510	STRABANE	89515	STRABANE PST	756	4902
89515	STRABANE PST	89516	STRABANE PST	32	1116
3581	LETTERKENNY	89516	STRABANE PST	32	1116

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[27] > 150% loading, denoted by “>>”, for the loading >105% and <150% the lines are denoted by “>”. The notation is valid for all tables in this Appendix.

Table E 4-Lines that frequently cause overloads – Winter Peak –Portfolio 2

Lines whose outage causes overloads					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of caused overloads >>**	**Number of caused overloads >**
1401	BELLACORICK	1661	CASTLEBAR	7151	5470
5141	TARBERT	5261	TRIEN	4345	3979
1931	CUNGHILL	4981	SLIGO	3197	1487
1651	CLAHANE	5281	TRALEE	2509	1589
2002	CULLENAGH	2742	GREAT ISLAND	758	8622
1701	CATHALLEN'S FALL	1981	CORRACLASSY	95	3297
1601	CLASHAVOON	1611	CLONKEEN	41	415

Winter Peak – Portfolio 5

Table E 5-Most frequently overloaded lines – Winter Peak-Portfolio 5

Overloaded lines					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of trials >>**	**Number of trials >**
1401	BELLACORICK	1661	CASTLEBAR	6475	1358
1931	CUNGHILL	4981	SLIGO	6475	1358
1931	CUNGHILL	4041	MOY	6264	1455
2001	CULLENAGH	5441	WATERFORD	5622	3357
5141	TARBERT	5261	TRIEN	2868	1823
1651	CLAHANE	5281	TRALEE	2717	1762
77510	DUNGANNON	87510	OMAGH	2603	2232
1401	BELLACORICK	4041	MOY	2208	3336
77510	DUNGANNON	87510	OMAGH1	2196	2337
1651	CLAHANE	5261	TRIEN	1840	1885
1481	BUTLERSTOWN	2001	CULLENAGH	1812	6559
89510	STRABANE	89515	STRABANE PST	1804	1946
89515	STRABANE PST	89516	STRABANE PST	1804	1946

Table E 6- Lines that frequently cause overloads – Winter Peak –Portfolio 5

Lines whose outage causes overloads					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of caused overloads>>**	**Number of caused overloads>**
3581	LETTERKENNY	89516	STRABANE PST	1748	1971
1401	BELLACORICK	1661	CASTLEBAR	13496	3933
1931	CUNGHILL	4981	SLIGO	7926	5292
2002	CULLENAGH	2742	GREAT ISLAND	7637	18015
1701	CATHALLEN'S FALL	1981	CORRACLASSY	5356	5880
5141	TARBERT	5261	TRIEN	4582	5139
77510	DUNGANNON	87510	OMAGH	2603	2232
77510	DUNGANNON	87510	OMAGH	2199	2825
1651	CLAHANE	5281	TRALEE	1600	1026
1601	CLASHAVOON	1611	CLONKEEN	1268	2109
1881	CHARLEVILLE	3281	KILLONAN	737	3595
89515	STRABANE PST	89516	STRABANE PST	323	2565
77010	DRUMNAKELLY	77510	DUNGANNON	301	2835
77010	DRUMNAKELLY	77510	DUNGANNON	301	2835
1881	CHARLEVILLE	4021	MALLOW	240	1740

Winter Peak - Portfolio 6

Table E 7- Most frequently overloaded lines – Winter Peak-Portfolio 6

Overloaded lines					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of trials >>**	**Number of trials >**
1401	BELLACORICK	1661	CASTLEBAR	8212	471
1931	CUNGHILL	4981	SLIGO	8212	471
1931	CUNGHILL	4041	MOY	7870	618
1401	BELLACORICK	4041	MOY	6882	740
89510	STRABANE	89515	STRABANE PST	5851	1285

Table E7cont--Most frequently overloaded lines – Winter Peak-Portfolio 6

Overloaded lines					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of trials >>**	**Number of trials >**
89515	STRABANE PST	89516	STRABANE PST	5851	1285
3581	LETTERKENNY	89516	STRABANE PST	5813	1292
1661	CASTLEBAR	1821	CLOON	5475	1072
2521	FLAGFORD	5341	TONROE	5202	1117
1661	CASTLEBAR	2281	DALTON	5189	1178
1181	ARVA	1861	CARRICK ON SHANNON	4783	2644
5141	TARBERT	5261	TRIEN	4756	1217
5281	TRALEE	43619	OUGHTRAGH TEE	4687	1624
1601	CLASHAVOON	1611	CLONKEEN	4660	1627

Table E 8- Lines that frequently cause overloads – Winter Peak –Portfolio 6

Lines whose outage causes overloads					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of caused overloads>>**	**Number of caused overloads>**
1401	BELLACORICK	1661	CASTLEBAR	13496	3933
1201	ARTANE	2561	FINGLAS URBAN	9680	0
1931	CUNGHILL	4981	SLIGO	7926	5292
2002	CULLENAGH	2742	GREAT ISLAND	7637	18015
1701	CATHALLEN'S FALLS	1981	CORRACLASSY	5356	5880
5141	TARBERT	5261	TRIEN	4582	5139
77510	DUNGANNON	87510	OMAGH	2603	2232
77510	DUNGANNON	87510	OMAGH	2199	2825
1651	CLAHANE	5281	TRALEE	1600	1026
1601	CLASHAVOON	1611	CLONKEEN	1268	2109
1881	CHARLEVILLE	3281	KILLONAN	737	3595
89515	STRABANE PST	89516	STRABANE PST	323	2565
77010	DRUMNAKELLY	77510	DUNGANNON	301	2835
77010	DRUMNAKELLY	77510	DUNGANNON	301	2835

Summer Maximum – Portfolio 1

Table E 9- Most frequently overloaded lines – Summer maximum-Portfolio 1

Overloaded lines					
Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Number of trials >>	Number of trials >
1401	BELLACORICK	1661	CASTLEBAR	1716	2029
1401	BELLACORICK	4041	MOY	1716	2029
1931	CUNGHILL	4981	SLIGO	1679	1679
1931	CUNGHILL	4041	MOY	905	1933

Table E 10- Lines that frequently cause overloads – Summer maximum –Portfolio 1

Lines whose outage causes overloads					
Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Number of caused overloads>>	Number of caused overloads>
1401	BELLACORICK	1661	CASTLEBAR	4300	5641
1931	CUNGHILL	4981	SLIGO	1503	0
1401	BELLACORICK	4041	MOY	213	2029

Summer Maximum – Portfolio 2

Table E 11- Most frequently overloaded lines – Summer maximum-Portfolio 2

Overloaded lines					
Bus 1 ID	Bus 1 Name	Bus 2 ID	Bus 2 Name	Number of trials>>	Number of trials>
1401	BELLACORICK	1661	CASTLEBAR	3970	1112
1931	CUNGHILL	4981	SLIGO	3970	1112
1931	CUNGHILL	4041	MOY	3636	1225
1651	CLAHANE-	5281	TRALEE	3086	1391
5141	TARBERT	5261	TRIEN	2546	1671
1651	CLAHANE	5261	TRIEN	2233	1650
1401	BELLACORICK	4041	MOY	2230	1888
2002	CULLENAGH	2742	GREAT ISLAND	1088	6412
2001	CULLENAGH	5441	WATERFORD	733	6453

Table E11cont - Most frequently overloaded lines – Summer maximum-Portfolio 2

Overloaded lines					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of trials>>**	**Number of trials>**
77510	DUNGANNON	87510	OMAGH	360	1986
77510	DUNGANNON	87510	OMAGH	171	1872
3581	LETTERKENNY	89516	STRABANE PST	89	1298
1881	CHARLEVILLE	3281	KILLONAN	46	2051

Table E 12- Lines that frequently cause overloads – Summer Maximum –Portfolio 2

Lines whose outage causes overloads					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of caused overloads >>**	**Number of caused overloads>**
1401	BELLACORICK	1661	CASTLEBAR	9836	4321
5141	TARBERT	5261	TRIEN	5322	4357
1931	CUNGHILL	4981	SLIGO	3970	1112
1651	CLAHANE-	5281	TRALEE	2024	1183
2002	CULLENAGH	2742	GREAT ISLAND	735	11291
1601	CLASHAVOON	1611	CLONKEEN	522	3065
77510	DUNGANNON	87510	OMAGH	360	1986
77510	DUNGANNON	87510	OMAGH	171	1891
1701	CATHALLEN'S FALLS	1981	CORRACLASSY	105	2639
1881	CHARLEVILLE	3281	KILLONAN	39	2980
1881	CHARLEVILLE	4021	MALLOW	38	1784
3202	KNOCKRAHA	3282	KILLONAN	8	461

Summer Maximum – Portfolio 5

Table E 13-Most frequently overloaded lines – Summer maximum-Portfolio 5

Overloaded lines					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of trials >>**	**Number of trials >**
1401	BELLACORICK	1661	CASTLEBAR	6732	1085
1931	CUNGHILL	4981	SLIGO	6732	1085
1921	COW CROSS	5481	WHITEGAT	6713	1894
1931	CUNGHILL	4041	MOY	6602	1162
1401	BELLACORICK	4041	MOY	4241	2528
2001	CULLENAGH	5441	WATERFOR	4176	3636
77510	DUNGANNON	87510	OMAGH	3766	1358
2002	CULLENAGH	2742	GREAT ISLAND	3642	4125
77510	DUNGANNON	87510	OMAGH	3491	1444
1881	CHARLEVILLE	3281	KILLONAN	3381	1471
1881	CHARLEVILLE	4021	MALLOW	3199	1354
3221	KILBARRY	4021	MALLOW	3132	1278
1651	CLAHANE	5281	TRALEE	3102	1338
5141	TARBERT	5261	TRIEN	2939	1494
77010	DRUMNAKELLY	77510	DUNGANNON	2574	1879

Table E 14-Lines that frequently cause overloads – Summer Maximum –Portfolio 5

Lines whose outage causes overloads					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of caused overloads>>**	**Number of caused overloads>**
1401	BELLACORICK	1661	CASTLEBAR	13609	8564
1931	CUNGHILL	4981	SLIGO	10945	10093
1881	CHARLEVILLE	3281	KILLONAN	6331	2597
5141	TARBERT	5261	TRIEN	6215	5806
2002	CULLENAGH	2742	GREAT ISLAND	5727	14548
1701	CATHALLEN'S FALLS	1981	CORRACLASSY	4522	5323

Table E14cont - Lines that frequently cause overloads – Summer Maximum –Portfolio 5

Lines whose outage causes overloads					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of caused overloads>>**	**Number of caused overloads>**
77510	DUNGANNON	87510	OMAGH	3878	3753
77510	DUNGANNON	87510	OMAGH	3766	1358
2204	DUNSTOWN	5494	WMD_400	3739	10210
3852	MAYNOOTH	4942	SHANNONBRIDGE	3351	3418
77010	DRUMNAKELLY	77510	DUNGANNON	2574	1879
77010	DRUMNAKELLY	77510	DUNGANNON	2574	1879
1601	CLASHAVOON	1611	CLONKEEN	2190	6217

Summer Maximum – Portfolio 6

Table E 15- Most frequently overloaded lines – Summer maximum-Portfolio 6A

Overloaded lines					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of trials >>**	**Number of trials >**
1401	BELLACORICK	1661	CASTLEBAR	6632	885
1931	CUNGHILL	4981	SLIGO	6632	785
1921	COW CROSS	5481	WHITEGATE	6413	1094
1931	CUNGHILL	4041	MOY	6302	862
1401	BELLACORICK	4041	MOY	4041	2028
2001	CULLENAGH	5441	WATERFORD	4276	3136
77510	DUNGANNON	87510	OMAGH	3366	958
2002	CULLENAGH	2742	GREAT ISLAND	3542	3825
77510	DUNGANNON	87510	OMAGH	3191	944
1881	CHARLEVILLE	3281	KILLONAN	3181	1071
1881	CHARLEVILLE	4021	MALLOW	2899	1254
3221	KILBARRY	4021	MALLOW	3032	978
1651	CLAHANE	5281	TRALEE	2802	938
5141	TARBERT	5261	TRIEN	2739	1294

Table E 16- Lines that frequently cause overloads – Summer Maximum –Portfolio 6A

Lines whose outage causes overloads					
Bus 1 ID	**Bus 1 Name**	**Bus 2 ID**	**Bus 2 Name**	**Number of caused overloads>>**	**Number of caused overloads>**
1401	BELLACORICK	1661	CASTLEBAR	12519	7564
1931	CUNGHILL	4981	SLIGO	9843	3733
1881	CHARLEVILLE	3281	KILLONAN	5831	1997
5141	TARBERT	5261	TRIEN	5735	4806
2002	CULLENAGH	2742	GREAT ISLAND	5135	2748
1701	CATHALLEN'S FALLS	1981	CORRACLASSY	4525	3578
77510	DUNGANNON	87510	OMAGH	3658	3753
77510	DUNGANNON	87510	OMAGH	3466	1488
2204	DUNSTOWN	5494	WMD_400	3339	7546
3852	MAYNOOTH	4942	SHANNONBRIDGE	3251	3418
77010	DRUMNAKELLY	77510	DUNGANNON	2654	1834
77010	DRUMNAKELLY	77510	DUNGANNON	2654	1834

Appendix F

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Portfolio 6A

F.1. The following new 220/275 kV substations are required to accommodate new renewable generation in Portfolio 6A:

Table F 1- New 220/275 kV substations-Portfolio 6A

New 220 kV substation	Voltage (kV)	Bus ID	Number of 220/110 transformers
BELLACORICK	220	1402	2
CUNGHILL	220	1932	1
MOY	220	4042	1
LETTERKENNY	275	3582	1
OMAGH	275	87511	2
TRILLICK	275	5362	1
STRBANE	275	89521	1
CLONKEEN	220	1612	1
TRIEN	220	9992	1
GLENLARA	220	2882	2
OUGHTRAGH	220	4362	1
BALLYLICKEY	220	1282	1
SHELTON ABBEY	220	4902	2

F.2. The following new 220/275 kV lines are required to accommodate new renewable generation in Portfolio 6A:

Table F 2- New 220/275 kV overhead lines-Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X[28](p.u.)	Rating(MVA) Winter/Summer
1402	BELLACORICK	4042	MOY	27.2	0.0236	2 lines, each (518/431)
4042	MOY	1932	CUNGHILL	41	0.0356	2 lines, each (518/431)
1932	CUNGHILL	5032	SRANANAGH	31	0.0269	2 lines, each (518/431)
5362	TRILLICK	3582	LETTERKENNY	35	0.0304	518/431

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[28] Reactance per unit values are given for a single circuit.

Table F2cont- New 220/275 kV overhead lines –Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Rating(MVA) Winter/Summer
89521	STRABANE	3582	LETTERKENNY	35	0.0304	518/431
89521	STRABANE	87511	OMAGH	37	0.0321	518/431
87511	OMAGH	90320	TYRONE	36	0.0312	518/431
89521	STRABANE	73521	COOLLKEERAGH	22	0.0191	518/431
5362	TRILLICK	73521	COOLKEERAGH	25	0.0217	518/431
5142	TARBERT	9992	TRIEN	21	0.0182	518/431
9992	TRIEN	2882	GLENLARA	46	0.0399	518/431
4362	OUGHTRAGH	9992	TRIEN	21	0.0182	518/431
2882	GLENLARA	1612	CLONKEEN	19	0.0165	518/431
1612	CLONKEEN	1602	CLASHAVOON	28	0.0243	518/431
[29]2002	CULLENAGH	2742	GREAT ISLAND	23	0.02	438/333
1282	BALLYLICKEY	4722	RAFFEEN	77	0.0673	518/431
4902	SHELTON ABBEY	1742	CARRICKMINES	53	0.0462	518/431
4902	SHELTON ABBEY	1122	ARKLOW	1	0.000868	518/431

F.3. The following new 110 kV lines should be built/uprated to accommodate new renewable generation in Portfolio 6A:

Table F 3- New/Uprated 110 kV overhead lines –Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Uprated/New	Rating(MVA) Winter/Summer
1121	ARKLOW	4901	SHELTON ABBEY	1	0.003248	New	168/145
5141	TARBERT	9991	TRIEN	20.5	0.0649	Uprated	168/145
75010	COLERAINE	84511	LOGUESTOWN	8	0.027	Uprated	168/145
75010	COLERAINE	84512	LOGUESTOWN	8	0.027	Uprated	168/145
75010	COLERAINE	81510	KELLS	59	0.0197	Uprated	168/145

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[29] A new 220 kV line from Cullenagh to Great Island is required as well as the uprating of the existing 220 kV line mainly due to severe overloads of the neighbouring 110 kV lines caused by an outage of the existing 220 kV line. For the new line the same rating was used as for the existing line.

Table F3cont- New/Uprated 110 kV lines –Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Uprated/New	Rating(MVA) Winter/Summer
1931	CUNGHILL	4981	SLIGO	20	0.065	Uprated	168/145
1931	CUNGHILL	4981	SLIGO	20	0.065	New	168/145
5181	MACROOM	3881	TRABEG	25	0.08	New	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	New	168/145
1861	CARRICK ON SHANNON	10619	ARIGNA TEE	21	0.0682	Uprated	168/145
1181	ARVA	1861	CARRICK ON SHANNON	41.4	0.142	Uprated	168/145
2521	FLAGFORD	4981	SLIGO	31	0.173	Uprated	126/116
2521	FLAGFORD	3501	LANESBORO	50.5	0.1	New	168/145

Portfolio 5

F.4. The following new 220/275 kV substations are required to accommodate new renewable generation in Portfolio 5:

Table F 4- New 220/275 kV substations-Portfolio 5

New 220 kV substation	Voltage (kV)	Bus ID	Number of 220/110 transformers
BELLACORICK	220	1402	1
CUNGHILL	220	1932	1
MOY	220	4042	1
STRABANE	275	89521	1
LETTERKENNY	275	3582	1
OMAGH	275	87511	2
TRILLICK	275	5362	1
CLONKEEN	220	1612	1
TRIEN	220	9992	1
GLENLARA	220	2882	2

F.5. The following new 220/275 kV lines are required to accommodate new renewable generation in Portfolio 5:

Table F 5- New 220/275 kV overhead lines –Portfolio 5

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**X(p.u.)**	**Rating(MVA) Winter/Summer**
1402	BELLACORICK	4042	MOY	27.2	0.0236	518/431
4042	MOY	1932	CUNGHILL	41	0.0356	2 lines, each 518/431
1932	CUNGHILL	5042	SRANANAGH	31	0.0269/2	2 lines, each (518/431)
5362	TRILLICK	3582	LETTERKENNY	35	0.0304	518/431
89521	STRABANE	3582	LETTERKENNY	35	0.0304	518/431
89521	STRABANE	87511	OMAGH	37	0.0321	518/431
87511	OMAGH	90320	TYRONE	36	0.0312	2 lines, each (518/431)
89521	STRABANE	73521	COOLKEERAGH	22	0.0191	518/431
5362	TRILLICK	73521	COOLKEERAGH	25	0.0217	518/431
5142	TARBERT	9992	TRIEN	21	0.0182	518/431
9982	TRIEN	2882	GLENLARA	46	0.0399	518/431
2882	GLENLARA	1612	CLONKEEN	19	0.0165	518/431
1612	CLONKEEN	1602	CLASHAVOON	28	0.0243	518/431
2002	CULLENAGH	2742	GREAT ISLAND	23	0.02	438/333

F.6. The following new 110 kV lines should be built/uprated to accommodate new renewable generation in Portfolio5:

Table F 6- New/Uprated 110 kV overhead lines –Portfolio 5

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**X(p.u.)**	**Uprated/New**	**Rating(MVA) Winter/Summer**
1181	ARVA	1861	CARRICK ON SHANNON	41.4	0.142	Uprated	168/145
1981	CORRACLASSY	2821	GORTAWEE	11	0.0371	Uprated	168/145
1481[30]	BUTLERSTOWN	2001	CULLENAGH	11.6	0.0398	New	126/116

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[30] This is not an overload caused by renewable generation, but it is a short new 110 kV line that helps avoiding other overloads between Cullenagh and Great Island.

Table F6cont- New/Uprated 110 kV overhead lines –Portfolio 5

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Uprated/New	Rating(MVA) Winter/Summer
5141	TARBERT	5261	TRIEN	20.5	0.0649	New	168/145
77010	DRUMNAKELLY	77510	DUNGANNON	25	0.0868	New	168/145
5181	MACROOM	3881	TRABEG	25	0.08	New	168/145
1861	CARRICK ON SHANNON	10619	ARIGNA TEE	21	0.0682	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	New	168/145
2321	DRUMKEEN	3581	LETTERKENNY	8	0.026	Uprated	168/145
4991	SORNE HILL	5361	TRILLICK	4.4	0.0143	Uprated	168/145
87510	OMAGH	77510	DUNGANNON	40	0.1242	New	126/116

Portfolios 4,3,2

F.7. The following new 220 kV substations are required to accommodate new renewable generation in Portfolio 4, Portfolio 3 and Portfolio 2:

Table F 7- New 220/275 kV substations-Portfolios 4,3,2

New 220 kV substation	Voltage (kV)	Bus ID	Number of 220/110 transformers
MOY	220	4041	1
LETTERKENNY	275	3582	1
OMAGH	275	87511	1
STRABANE	275	89521	1
CLONKEEN	220	1612	1
TRIEN	220	9992	1

F.8. The following new 220/275 kV lines are required to accommodate new renewable generation in portfolios 4,3,2:

Table F 8- New 220/275 kV overhead lines –Portfolios 4,3,2

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Rating(MVA) Winter/Summer
4042	MOY	5042	SRANANAGH	72	0.0625	518/431
89521	STRABANE	3582	LETTERKENNY	35	0.0304	2 lines, each (518/431)
89521	STRABANE	87511	OMAGH	37	0.0321	518/431
87511	OMAGH	90320	TYRONE	36	0.0312	518/431
89521	STRABANE	73521	COOLLKEERAGH	22	0.0191	518/431
5142	TARBERT	9992	TRIEN	21	0.0182	518/431
9992	TRIEN	1612	CLONKEEN	65	0.0399	518/431
1612	CLONKEEN	1602	CLASHAVOON	28	0.0243	518/431
2002	CULLENAGH	2742	GREAT ISLAND	23	0.02	438/333

F.9. The following new 110 kV lines should be built/uprated to accommodate new renewable generation in Portfolio 2, Portfolio 3 and Portfolio 4:

Table F 9- New/Uprated 110 kV overhead lines –Portfolios 4,3,2

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Uprated/New	Rating(MVA) Winter/Summer
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	New	168/145
5141	TARBERT	9991	TRIEN	20.5	0.0649	New	168/145
3881	MACROOM	5181	TRABEG	25	0.08	New	168/145
1601	CLASHAVOON	3881	MACROOM	6	0.018	New	223/187
1481	BUTLERSTOWN	2001	CULLENAGH	11.6	0.0398	New	126/116

F.10. It should be pointed out that 110 kV lines: Clonkeen to Coomageralhy can be overloaded for the summer maximum operational regime considering that its line rating is 187 MVA and the total wind power injection at Coomagearlahy and Glanlee is 198 MW. An outage of the 220 kV line Clonkeen to Clashavoon or the Clonkeen 220/110 transformer will cause an overload of the 110 kV line Clashavoon to Clonkeen.

Portfolio 1

F.11. The following new 110 kV lines should be built/uprated to accommodate new renewable generation in Portfolio 1:

Table F 10- New/Uprated 110 kV overhead lines –Portfolio 1

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Uprated/New	Rating(MVA) Winter/Summer
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	New	168/145

Appendix G

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Portfolio 6A

G.1. The list of new 220/275 kV substations suggested in Task 1 (see *Table F 1*) is changed (transformers Letterkenny and Trillick). Therefore, the final list on the new 220/275 kV substation is given in the following table for Portfolio 6A:

Table G 1- Final list of new 220/275 kV substations-Portfolio 6A

New 220 kV substation	Voltage (kV)	Bus ID	Number of 220/110 transformers
BELLACORICK	220	1402	2
CUNGHILL	220	1932	1
MOY	220	4042	1
LETTERKENNY	275	3582	2
OMAGH	275	87511	2
TRILLICK	275	5362	2
STRBANE	275	89521	1
CLONKEEN	220	1612	1
TRIEN	220	9992	1
GLENLARA	220	2882	2
OUGHTRAGH	220	4362	1
BALLYLICKEY	220	1282	1
SHELTON ABBEY	220	4902	2

G.2. The list of new 220/275 kV lines suggested in Task 1 is not changed. The final list of the new 220/275 kV lines is given in the following table for Portfolio 6A:

Table G 2- Final list of new/uprated 220/275 kV overhead lines-Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	Rating(MVA) Winter/Summer
1402	BELLACORICK	4042	MOY	27.2	2 lines, each (518/431)
4042	MOY	1932	CUNGHILL	41	2 lines, each (518/431)
1932	CUNGHILL	5032	SRANANAGH	31	2 lines, each (518/431)
5362	TRILLICK	3582	LETTERKENNY	35	518/431

Table G2cont- Final list of new/uprated 220/275 kV overhead lines-Portfolio 6A

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**Rating(MVA) Winter/Summer**
89521	STRABANE	3582	LETTERKENNY	35	518/431
89521	STRABANE	87511	OMAGH	37	518/431
87511	OMAGH	90320	TYRONE	36	518/431
89521	STRABANE	73521	COOLLKEERAGH	22	518/431
5362	TRILLICK	73521	COOLKEERAGH	25	518/431
5142	TARBERT	9992	TRIEN	21	518/431
9992	TRIEN	2882	GLENLARA	46	518/431
4362	OUGHTRAGH	9992	TRIEN	21	518/431
2882	GLENLARA	1612	CLONKEEN	19	518/431
1612	CLONKEEN	1602	CLASHAVOON	28	518/431
1282	BALLYLICKEY	4722	RAFFEEN	77	518/431
4902	SHELTON ABBEY	1742	CARRICKMINES	53	518/431
4902	SHELTON ABBEY	1122	ARKLOW	1	518/431

G.3. The list of new 110 kV lines suggested in Task 1 (see *Table F 3*) is changed. The final list of the new 110 kV lines is given in the following table for Portfolio 6A:

Table G 3- Final list of new/uprated 110 kV overhead lines –Portfolio 6A

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**X(p.u.)**	**Uprated/New**	**Rating(MVA) Winter/Summer**
1121	ARKLOW	4901	SHELTON ABBEY	1	0.003248	New	168/145
75010	COLERAINE	84511	LOGUESTOWN	8	0.027	Uprated	168/145
75010	COLERAINE	84512	LOGUESTOWN	8	0.027	Uprated	168/145
75010	COLERAINE	81510	KELLS	59	0.0197	Uprated	168/145
1931	CUNGHILL	4981	SLIGO	20	0.065	Uprated	168/145
1931	CUNGHILL	4981	SLIGO	20	0.065	New	168/145
5181	MACROOM	3881	TRABEG	25	New	168/145	5181
1401	BELLACORICK	1661	CASTLEBAR	37.4	Uprated	168/145	1401
1401	BELLACORICK	1661	CASTLEBAR	37.4	New	168/145	1401
1861	CARRICK ON SHANNON	10619	ARIGNA TEE	21	Uprated	168/145	1861

Table G3cont- Final list of new/uprated 110 kV overhead lines –Portfolio 6A

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Uprated/New	Rating(MVA) Winter/Summer
1181	ARVA	1861	CARRICK ON SHANNON	41.4	Uprated	168/145	1181
2521	FLAGFORD	4981	SLIGO	31	Uprated	126/116	2521
2521	FLAGFORD	3501	LANESBORO	50.5	New	168/145	2521
4361	OUGHTRATGH	43619	OUGHTRAGH TEE	11	New	168/145	4361
3581	LETTERKENY	5361	TRILLICK	35	New	168/145	3581
1651	CLAHANE	5261	TRIEN	9	New	168/145	1651
1861	CARRICK ON SHANNON	2521	FLAGFORD	3.4	New	168/145	1861
1281	BALLILICKEY	2221	DUNMANWAY	28	Uprated	168/145	1281
5141	TARBERT	5261	TRIEN	20.5	New	168/145	5141
4991	SORNE HILL	5361	TRILLICK	4.4	New	168/145	4991
1121	ARKLOW	4911	SHELTON	1	New	2X(168/145)	1121

Portfolio 6B

G.4. The list of new 220/275 kV substations is given in the following table for Portfolio 6B:

Table G 4 *-Final list of new/ 220/275 kV substations-Portfolio 6B*

New 220 kV substation	Voltage (kV)	Bus ID	Number of 220/110 transformers
BELLACORICK	220	1402	1
CUNGHILL	220	1932	1
MOY	220	4042	1
STRBANE	220	89521	1
LETTERKENNY	275	3582	2
OMAGH	275	87511	2
TRILLICK	275	5362	2
CLONKEEN	220	1612	1
TRIEN	220	9992	1
GLENLARA	220	2882	2

G.5. The list of new 220/275 kV lines is given in the following table for Portfolio 6B:

Table G 5- Final list of new/uprated 220/275 kV overhead lines –Portfolio 6B

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**Rating(MVA) Winter/Summer**
1402	BELLACORICK	4042	MOY	27.2	518/431
4042	MOY	1932	CUNGHILL	41	2 lines, each 518/431
1932	CUNGHILL	5042	SRANANAGH	31	2 lines, each (518/431)
5362	TRILLICK	3582	LETTERKENNY	35	518/431
89521	STRABANE	3582	LETTERKENNY	35	518/431
89521	STRABANE	87511	OMAGH	37	518/431
87511	OMAGH	90320	TYRONE	36	2 lines, each (518/431)
89521	STRABANE	73521	COOLKEERAGH	22	518/431
5362	TRILLICK	73521	COOLKEERAGH	25	518/431
5142	TARBERT	9992	TRIEN	21	518/431
9982	TRIEN	2882	GLENLARA	46	518/431
2882	GLENLARA	1612	CLONKEEN	19	518/431
1612	CLONKEEN	1602	CLASHAVOON	28	518/431
2002	CULLENAGH	2742	GREAT ISLAND	23	438/333

G.6. The list of new/uprated 110 kV lines is given in the following table for Portfolio 6B:

Table G 6- Final list of new/uprated 110 kV overhead lines –Portfolio 6B

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**Uprated/New**	**Rating(MVA) Winter/Summer**
1181	ARVA	1861	CARRICK ON SHANNON	41.4	Uprated	168/145
1981	CORRACLASSY	2821	GORTAWEE	11	Uprated	168/145
1481	BUTLERSTOWN	2001	CULLENAGH	11.6	New	126/116
5141	TARBERT	5261	TRIEN	20.5	New	168/145
77010	DRUMNAKELLY	77510	DUNGANNON	25	New	168/145
5181	MACROOM	3881	TRABEG	25	New	168/145

Table G6cont- Final list of new/uprated 110 kV overhead lines –Portfolio 6B

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	Uprated/New	Rating(MVA) Winter/Summer
1861	CARRICK ON SHANNON	10619	ARIGNA TEE	21	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	New	168/145
2321	DRUMKEEN	3581	LETTERKENNY	8	Uprated	168/145
4991	SORNE HILL	5361	TRILLICK	4.4	Uprated	168/145
87510	OMAGH	77510	DUNGANNON	40	New	126/116
4361	OUGHTRATGH	43619	OUGHTRAGH TEE	11	New	168/145
1281	BALLILICKEY	2221	DUNMANWAY	28	Uprated	168/145
1281	BALLILICKEY	2221	DUNMANWAY	28	New	168/145
1181	ARVA	1861	CARRICK ON SHANNON	41.4	New	168/145
3581	LETTERKENY	5361	TRILLICK	35	New	168/145
1931	CUNGHILL	4981	SLIGO	20	Uprated	168/145
1931	CUNGHILL	4981	SLIGO	20	New	168/145
2521	FLAGFORD	4981	SLIGO	31	Uprated	126/116
1861	CARRICK ON SHANNON	10619	ARIGNA TEE	21	New	168/145
1881	CHARLEVILLE	2881	GLENLARA	30	Uprated	168/145

Portfolio 5

G.7. The list of new 220/275 kV substations suggested in Task 1(see *Table F 4*) is changed (Letterkenny). Therefore, the final list on the new 220/275 kV substation is given in the following table for Portfolio 5:

Table G 7- Final list of new 220/275 kV substations-Portfolio 5

New 220 kV substation	Voltage (kV)	Bus ID	Number of 220/110 transformers
BELLACORICK	220	1402	1
CUNGHILL	220	1932	1
MOY	220	4042	1
STRBANE	220	89521	1
LETTERKENNY	275	3582	2
OMAGH	275	87511	2
TRILLICK	275	5362	1
CLONKEEN	220	1612	1
TRIEN	220	9992	1
GLENLARA	220	2882	2

G.8. The list of new 220/275 kV lines suggested in Task 1 is not changed. The final list of the new 220/275 kV lines is given in the following table for Portfolio 5:

Table G 8- Final list of new/uprated 220/275 kV overhead lines –Portfolio 5

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	Rating(MVA) Winter/Summer
1402	BELLACORICK	4042	MOY	27.2	518/431
4042	MOY	1932	CUNGHILL	41	2 lines, each 518/431
1932	CUNGHILL	5042	SRANANAGH	31	2 lines, each (518/431)
5362	TRILLICK	3582	LETTERKENNY	35	518/431
89521	STRABANE	3582	LETTERKENNY	35	518/431
89521	STRABANE	87511	OMAGH	37	518/431
87511	OMAGH	90320	TYRONE	36	2 lines, each (518/431)
89521	STRABANE	73521	COOLKEERAGH	22	518/431

Table G8cont- Final list of new/uprated 220/275 kV overhead lines –Portfolio 5

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**Rating(MVA) Winter/Summer**
5362	TRILLICK	73521	COOLKEERAGH	25	518/431
5142	TARBERT	9992	TRIEN	21	518/431
9982	TRIEN	2882	GLENLARA	46	518/431
2882	GLENLARA	1612	CLONKEEN	19	518/431
1612	CLONKEEN	1602	CLASHAVOON	28	518/431
2002	CULLENAGH	2742	GREAT ISLAND	23	438/333

G.9. The list of new/uprated 110 kV lines suggested in Task 1(see *Table F 6*) <u>is changed</u>. Therefore, the final list on the new 110 and 110 kV lines is given in the following table for Portfolio 5:

Table G 9- Final list of new/uprated 110 kV overhead lines –Portfolio 5

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**Uprated/New**	**Rating(MVA) Winter/Summer**
1181	ARVA	1861	CARRICK ON SHANNON	41.4	Uprated	168/145
1981	CORRACLASSY	2821	GORTAWEE	11	Uprated	168/145
1481	BUTLERSTOWN	2001	CULLENAGH	11.6	New	126/116
5141	TARBERT	5261	TRIEN	20.5	New	168/145
77010	DRUMNAKELLY	77510	DUNGANNON	25	New	168/145
5181	MACROOM	3881	TRABEG	25	New	168/145
1861	CARRICK ON SHANNON	10619	ARIGNA TEE	21	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	New	168/145
2321	DRUMKEEN	3581	LETTERKENNY	8	Uprated	168/145
4991	SORNE HILL	5361	TRILLICK	4.4	Uprated	168/145
87510	OMAGH	77510	DUNGANNON	40	New	126/116

Table G9cont - Final list of new/uprated 110 kV overhead lines –Portfolio 5

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	Uprated/New	Rating(MVA) Winter/Summer
79010	ENNISKILLEN	87510	OMAGH	34	New	126/116
1881	CHARLEVILLE	3281	KILLONAN	37	Uprated	168/145
3581	LETTERKENY	5361	TRILLICK	35	New	168/145
1881	CHARLEVILLE	2881	GLENLARA	30	Uprated	168/145

Portfolios 4,3,2

G.10. The list of new 220/275 kV substations suggested in Task 1 is not changed. Therefore, the final list on the new 220/275 kV substation is given in the following table for Portfolio 4, Portfolio 3 and Portfolio 2:

Table G 10- Final list of new/uprated 220/275 kV substations list-Portfolios 4,3,2

New 220 kV substation	Voltage (kV)	Bus ID	Number of 220/110 transformers
MOY	220	4041	1
LETTERKENNY	275	3582	1
OMAGH	275	87511	1
STRABANE	275	89521	1
CLONKEEN	220	1612	1
TRIEN	220	9992	1

G.11. The list of new 220/275 kV lines suggested in Task 1 is not changed. Therefore, the final list on the new 220/275 kV lines is given in the following table for Portfolio 4, Portfolio 3 and Portfolio 2:

Table G 11- Final list of new/uprated 220/275 kV overhead lines –Portfolios 4,3,2

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	Rating(MVA) Winter/Summer
4042	MOY	5042	SRANANAGH	72	518/431
89521	STRABANE	3582	LETTERKENNY	35	2 lines, each (518/431)
89521	STRABANE	87511	OMAGH	37	518/431
87511	OMAGH	90320	TYRONE	36	518/431
89521	STRABANE	73521	COOLLKEERAGH	22	518/431

Table G11cont - Final list of new/uprated 220/275 kV overhead lines –Portfolios 4,3,2

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**Rating(MVA) Winter/Summer**
5142	TARBERT	9992	TRIEN	21	518/431
9992	TRIEN	1612	CLONKEEN	65	518/431
1612	CLONKEEN	1602	CLASHAVOON	28	518/431
2002	CULLENAGH	2742	GREAT ISLAND	23	438/333

G.12. The list of new/uprated 110 kV lines suggested in Task 1(see *Table F 9*) is changed. Therefore, the final list on the new 110 kV lines is given in the following table for Portfolio 4, Portfolio 3 and Portfolio 2:

Table G 12- Final list of new/uprated 110 overhead lines –Portfolios 4,3,2

Bus1 ID	**Bus1 Name**	**Bus2 ID**	**Bus2 Name**	**Length(km)**	**Uprated/New**	**Rating(MVA) Winter/Summer**
1401	BELLACORICK	1661	CASTLEBAR	37.4	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	New	168/145
5141	TARBERT	9991	TRIEN	20.5	New	168/145
3881	MACROOM	5181	TRABEG	25	New	168/145
1601	CLASHAVOON	3881	MACROOM	6	New	223/187
1481	BUTLERSTOWN	2001	CULLENAGH	11.6	New	126/116
1881	CHARLEVILLE	2881	GLENALARA	30	New	168/145
1881	CHARLEVILLE	2881	GLENLARA	30	Uprated	168/145
1881	CHARLEVILLE	4021	MALLOW	22.5	New	168/145
1881	CHARLEVILLE	4021	MALLOW	22.5	Uprated	168/145
3221	KILBARY	4021	MALLOW	29	New	168/145
1931	CUNHGILL	4981	SLIGO	20	Uprated	168/145
5141	TARBERT	5261	TRIEN	20	Uprated	168/145
3281	KILLONAN	3541	LIMERICK	12	Uprated	168/145
3281	KILLONAN	3541	LIMERICK	12	Uprated	168/145
1881	CHARLEVILLE	3281	KILLONAN	37	Uprated	168/145

Portfolio 1

G.13. The list of new/uprated 110 kV lines suggested in Task 1 is not changed. Therefore, the final list on the new 110 kV lines is given in the following table for Portfolio 1:

Table G 13- Final list of new/uprated 110 kV overhead lines –Portfolio 1

Bus1 ID	Bus1 Name	Bus2 ID	Bus2 Name	Length(km)	X(p.u.)	Uprated/New	Rating(MVA) Winter/Summer
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	Uprated	168/145
1401	BELLACORICK	1661	CASTLEBAR	37.4	0.1215	New	168/145

Appendix H

Disclaimer

The purpose of the network diagrams presented in the following appendices is only to illustrate the envisaged network reinforcements between 2007 and 2020, intact system network flows, the identified network overloads and the proposed network reinforcements. It should be pointed out that the network data used for the study were obtained directly from the TSOs and it might be some discrepancies between this data and the network diagrams herein.

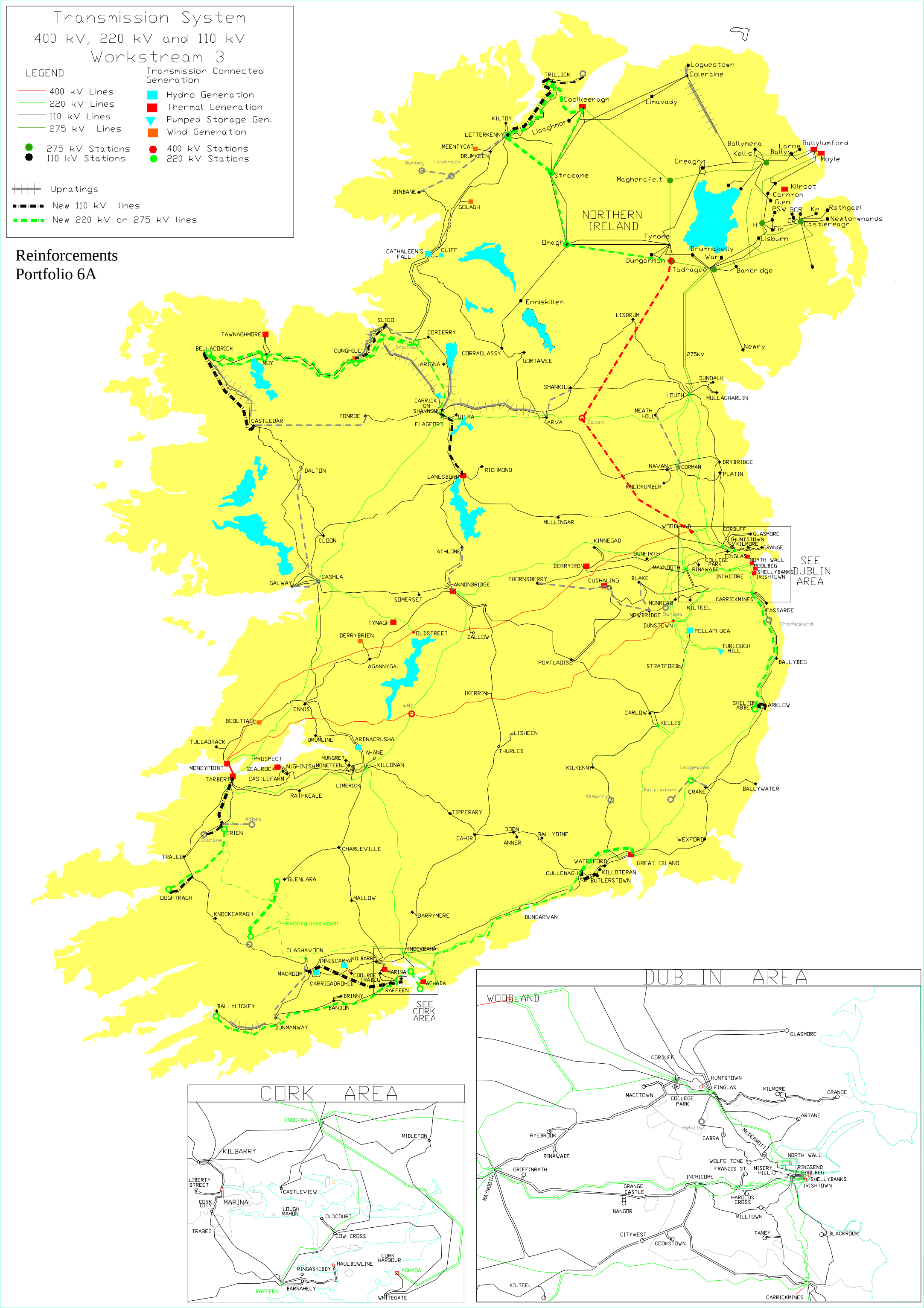

Figure H1- Network Reinforcements – Portfolio 6A

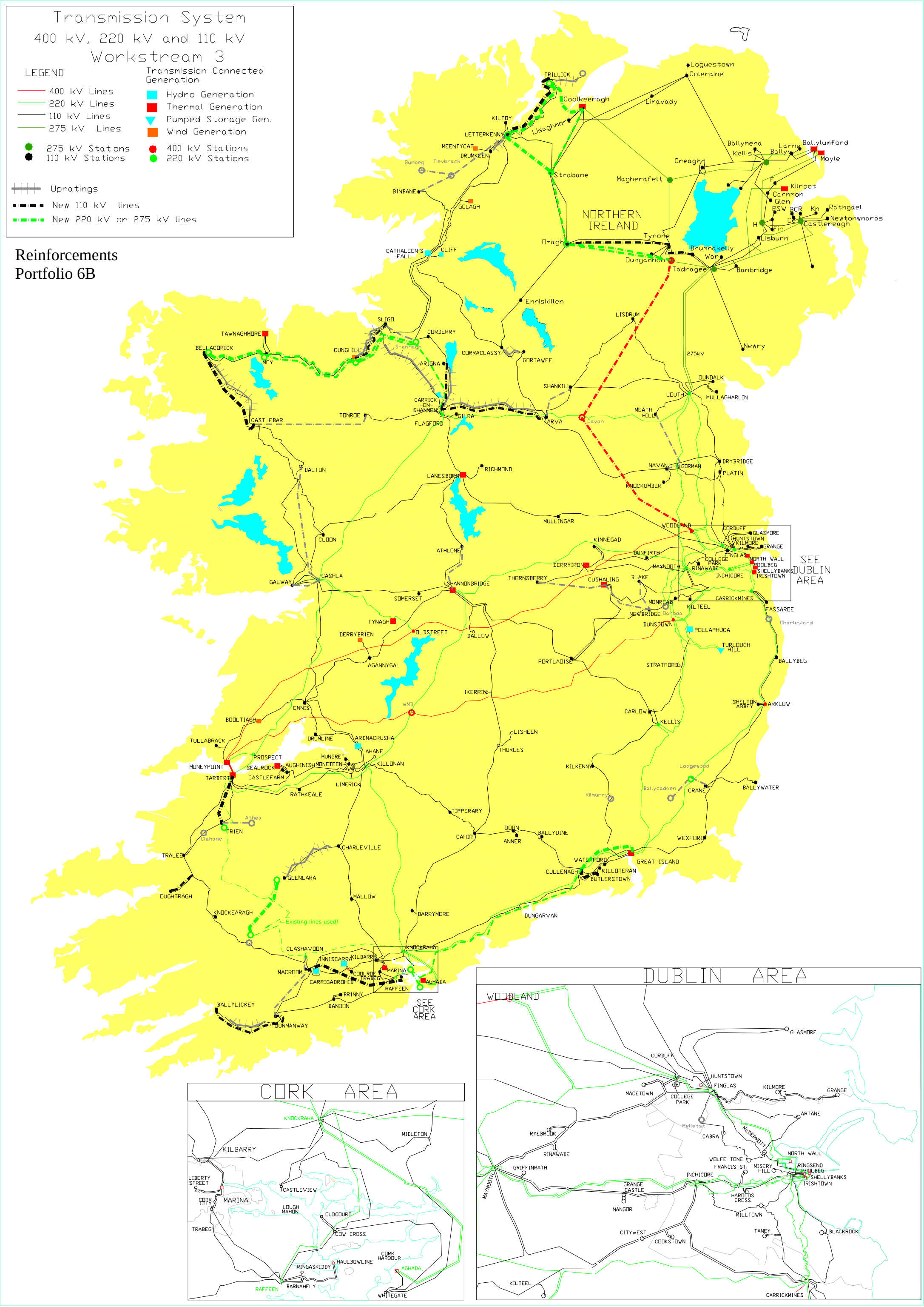

Figure H2- Network Reinforcements - Portfolio 6B

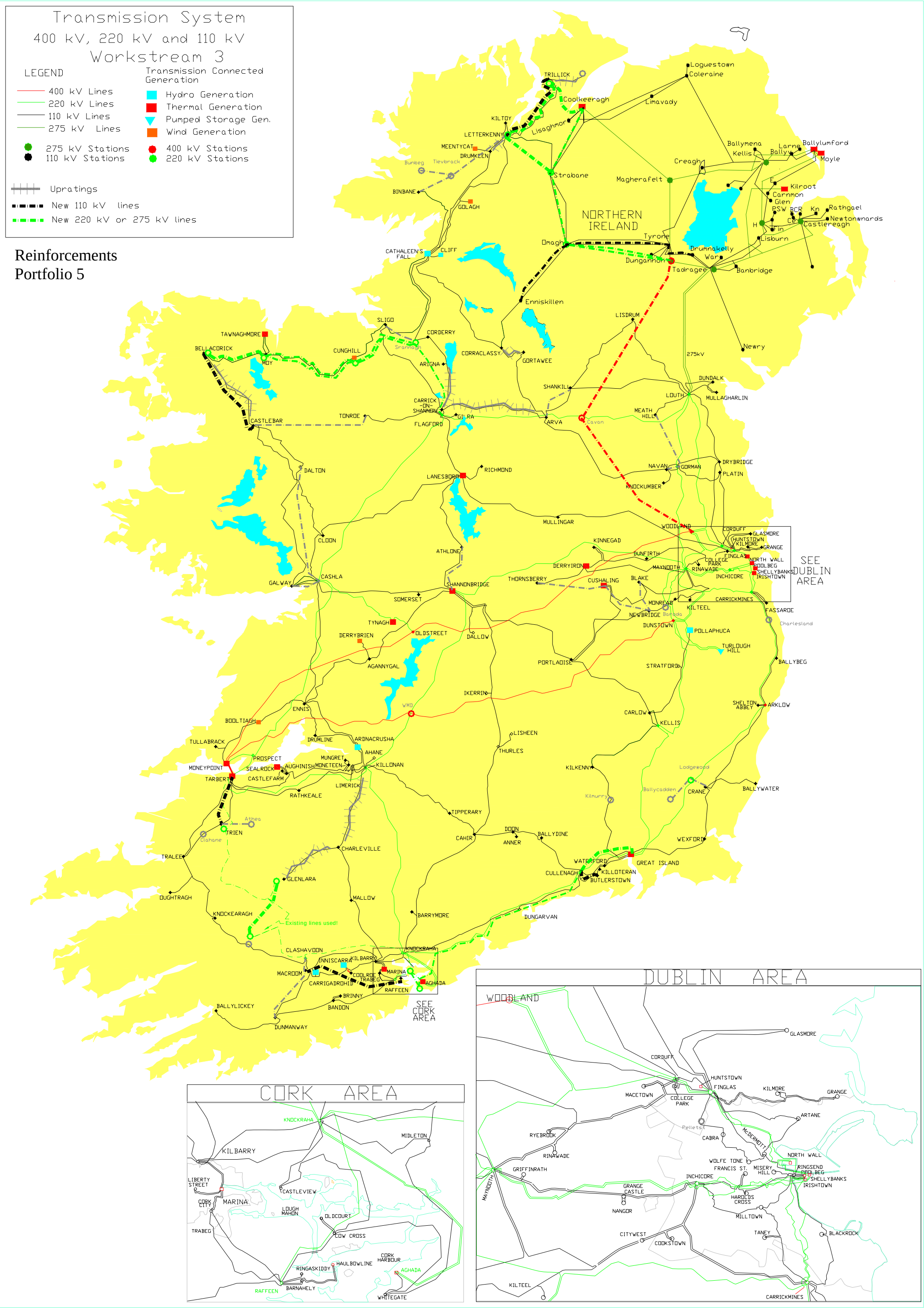

Figure H3- Network Reinforcements – Portfolio5

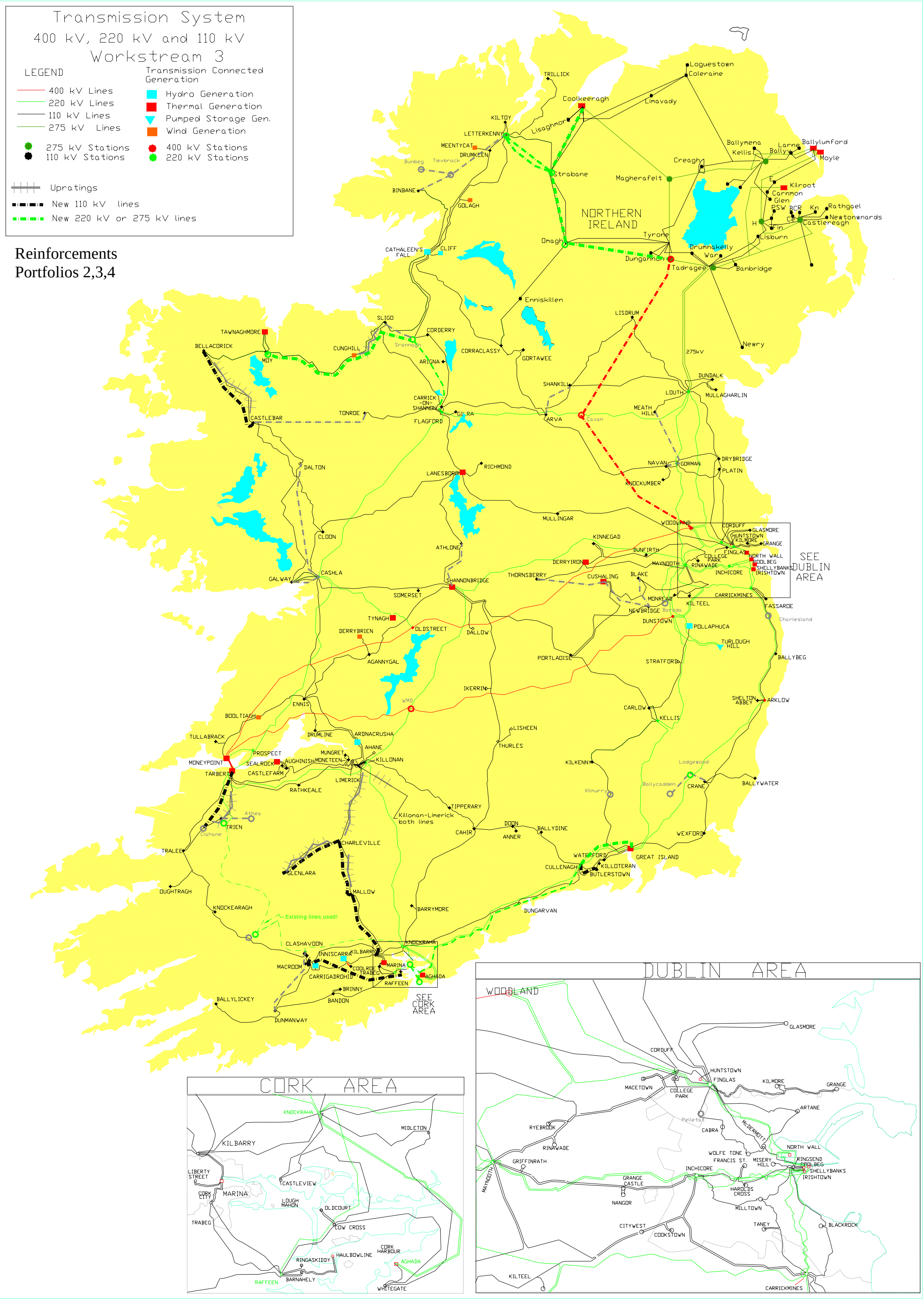

Figure H4- Network Reinforcements – Portfolios 2,3 and 4

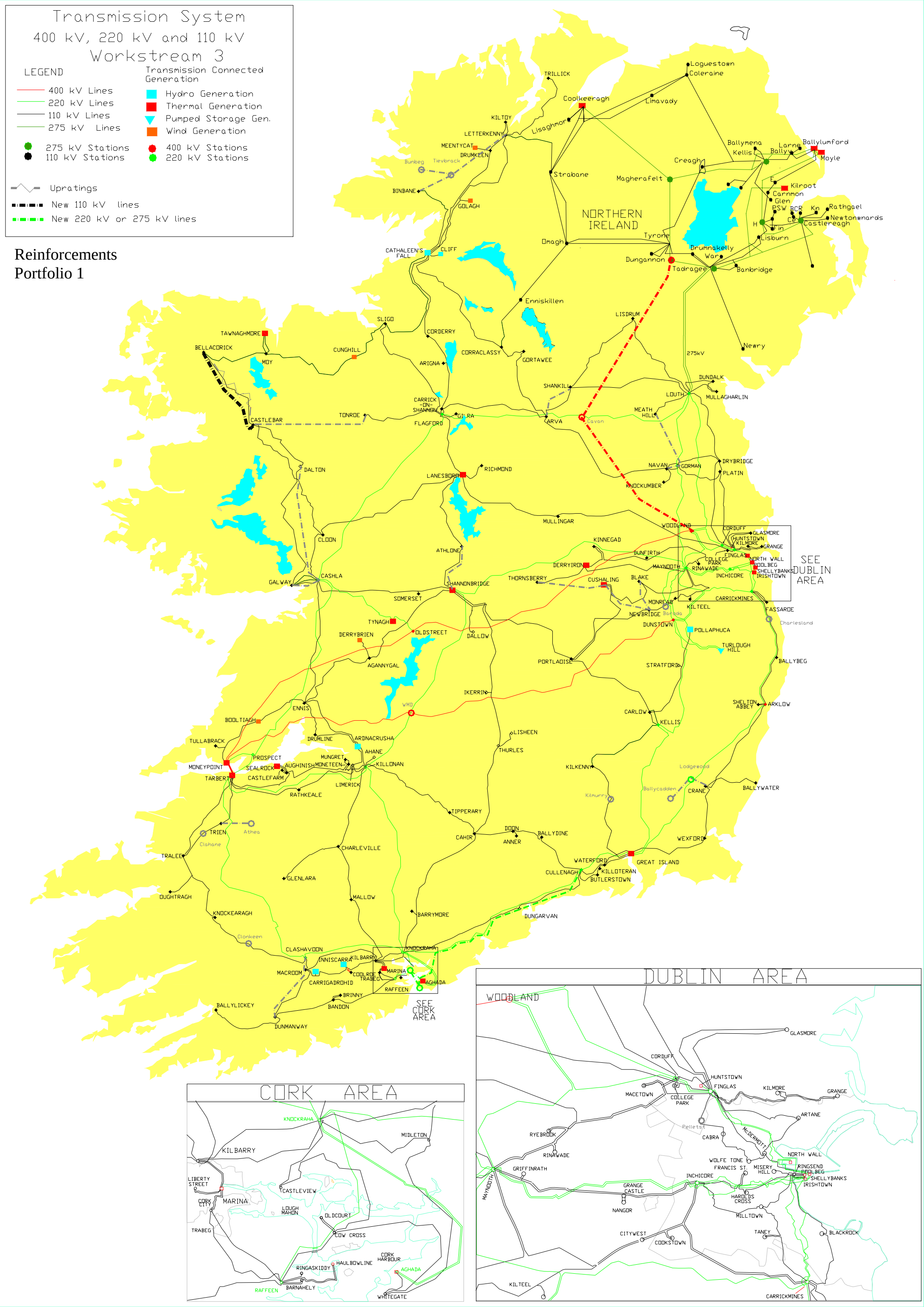

Figure H5 Network Reinforcements – Portfolios 1