A Methodology to Analyze the Economic Viability of a DC Transmission Grid with Onshore and Offshore Terminals

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ABSTRACT

This thesis aims to build a tool for network planners to design large-scale direct current (DC) grids that can link isolated alternative current (AC) grids to large AC grids, integrate offshore wind resources and transmit bulk power between large AC grids. Traditional high-voltage direct current (HVDC) systems usually consist of only point-to-point electricity transmission and do not allow connecting multiple branches on a single node. In this thesis, we build an approach that designs a large-scale HVDC grid and computes power flow for given parameters, which is then resolved as a mixed-integer non-linear programming (MINLP) optimization problem. To find a solution efficiently so that network planners can use the model on an everyday basis, we split the problem in two parts: the design of the DC grid as a mixed-integer linear programming (MILP) problem, and the actual power flow computation of the DC grid as a non-linear programming (NLP) problem.

While analyzing cases built by the model, we note that the linear part of the model (MILP, Planning approach) can choose DC links to optimize the design of large-scale DC grids and that the non-linear part (NLP, Operations approach) can compute the DC power flow accurately and yields precise power flow and power losses values. We also note that large-scale DC grids are more reliable than a single DC link. We then refine the design of the DC components of the system (voltage level and cable size) and include examples of economic analyses to show that DC grids that interconnect two large AC networks should exhibit a larger load factor, which should result in better economic performance than links between a small isolated AC grid and a larger AC grid. Finally, we suggest further research to improve the model to make it even more useful. Network planners will use DC grids in the future to integrate renewable energy sources in AC grids; they will need efficient tools to optimize the DC grid designing and planning process. This thesis provides such a tool and proposes further research to improve it.

RÉSUMÉ

Cette thèse vise à bâtir un outil pour les planificateurs de réseaux afin de concevoir des réseaux maillés à courant continu (CC) qui peuvent relier des réseaux autonomes à courant alternatif (CA) à de grands réseaux CA, intégrer des éoliennes en mer et transporter de grandes quantités d'énergie entre de grands réseaux CA. Les systèmes à courant continu haute tension (CCHT) ne permettent normalement que de transporter l'électricité d'un point à un autre et ne permettent pas de brancher plusieurs liens au même nœud. Dans cette thèse, nous construisons un modèle pour concevoir un réseau CCHT de grande ampleur et calculer la répartition de la puissance selon des paramètres prédéfinis, ce qui constitue un problème d'optimisation non linéaire en nombres entiers. Pour trouver rapidement une solution et rendre le modèle utile aux planificateurs, nous séparons le problème en deux parties : la conception du réseau, un problème d'optimisation linéaire en nombres entiers, et le calcul de la répartition de la puissance, un problème d'optimisation non linéaire.

En analysant les réseaux conçus par le modèle, nous notons que la portion linéaire du modèle optimise les liens CC à construire et que la portion non linéaire calcule précisément la répartition de la puissance ainsi les pertes électriques pour chaque lien. Nous notons que les réseaux très étendus sont plus fiables que de simples liens CC isolés. Nous raffinons ensuite la conception des équipements du système (niveau de tension et choix du câble) et incluons des exemples d'études économiques qui montrent qu'un réseau CC qui lie deux grands réseaux CA démontre un plus grand facteur d'utilisation, ce qui devrait donner un profit plus grand comparativement à un lien entre un petit réseau isolé CA et un plus grand réseau CA. Finalement, nous suggérons des sujets de recherche afin de rendre le modèle encore plus utile. Les planificateurs vont utiliser de plus en plus les réseaux CC pour intégrer de nouvelles énergies renouvelables ; ils auront besoin d'outils efficaces pour optimiser le processus de planification concernant les réseaux CC. Cette thèse fourni un tel outil et propose d'autres avenues pour l'améliorer.

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1 INTRODUCTION

Power systems planners and operators are facing numerous new challenges nowadays. Until the beginning of the 2000s, electricity generation usually involved burning fossil fuels or letting water flow in a controlled manner. Electricity transmission, which links the power generating units with distribution substations, could be programmed quite predictably. Power system planners and operators are now facing numerous new challenges. With more non-conventional wind and solar power generation (which is intermittent and often far from load centers) comes new transmission system planning challenges. Greenhouse gas emissions reduction policies are applying great pressure on power generation companies to make them adopt renewable ways of generating electricity, but that certainly results in power systems whose planning and operation have to be revisited. Moreover, large-scale renewable resources are rarely located near the load, so power lines must now cross international and interstate borders and need to interconnect asynchronous AC grids operated by different independent system operators. The design and implementation of bulk power transmission projects that can help clean energy get to very high penetration levels require imaginative solutions to all sorts of political, economic and technical challenges.

Like puzzle pieces falling in place, multiple conditions are met for system planners to consider building offshore DC systems. New developments in high-voltage direct current (HVDC), a need for clean energy sources and the growing difficulty to site overhead power lines have inspired us to consider the design of offshore DC systems to integrate clean generation and transmit bulk power.

The states of the Northeastern United States have declared their intention to dramatically reduce their greenhouse gas emissions by mid-century [1]. Recent HVDC developments can help to transmit clean power to load centers. The New Hampshire SEC (Site Evaluation Committee) recently denied an essential permit to the promoter of the Northern Pass Project, Eversource Energy. The committee stated that the promoter "*has failed to prove by a preponderance of the evidence that the Site and Facility, the Project, will* *not unduly interfere with the orderly development of the region, with due consideration having been given to the views of municipal and regional planning commissions and municipal governing bodies.*" [2] The social acceptance of large transmission line projects is a strategic issue for transmission system owners.

These are North American examples, but these conditions are also true in Europe. Figure 1 shows that dozens of HVDC projects are currently planned in Europe. Many of these projects are linked with the need to better pool renewable resources on a continental scale to ease global balance of supply and demand.

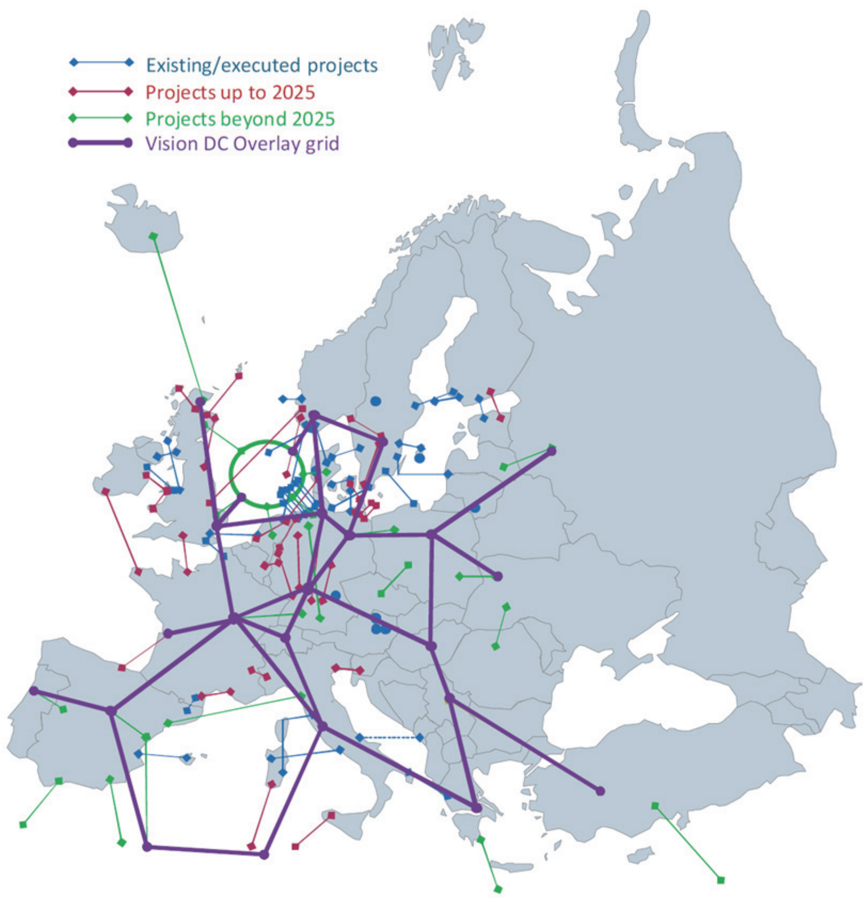

Figure 1 – Existing and planned DC connection in Europe with vision of DC overlay grid [3]

In North America, these recent events have shown that an offshore HVDC transmission grid in the Gulf of St. Lawrence and the eastern seaboard is of interest:

- The launch of two RFP (requests for proposals) for clean energy, 83C for offshore wind energy generation and 83D for clean energy by the State of Massachusetts [4]
- The recent commissioning of the Maritime Link by Emera, an HVDC submarine link between Newfoundland and Nova Scotia [5]
- The bid named “Atlantic Link” by Emera submitted to the Massachusetts RFP, currently at the permitting phase, plans to link New Brunswick and Massachusetts [6]
- The announcement that Hydro-Québec will connect the Magdalen Islands to the mainland using a submarine cable [7].

These events all show that there is interest in building HVDC submarine cables in the Northeast region of North America to answer the region’s need for clean electricity.

1.1 Background

Generating and transmitting electrical power is an activity that requires space and energy. Geographical regions have different ways to fulfill electricity demands and each power plant type has its advantages and its disadvantages. A generator may be controllable, cheap, clean or sited near the load, but it rarely meets all these characteristics. Intermittent generation, such as wind and solar, fulfills some of these advantages but must be backed by controllable generation, such as thermal or hydro.

System operators use an optimization process to find the economic dispatch given a pool of generators connected to their grids. Interconnecting electrical systems give the operator a larger pool of generators, which will result in a better dispatch for the new, larger system than what the operators were able to achieve for the two systems separately. System operators can use interconnections to reduce generation cost but also to increase the penetration of renewable energy, maximise its use and, therefore, minimize CO_2 emissions.

Most recently, one prominent topic in power engineering is the generation of clean electricity and its integration into power grids. Even clean generators have an impact on their environment. For example, wind turbines have a visual impact on landscapes and one cannot install them in densely populated areas. To minimize the impact of these generators, a solution is to install wind farms beyond the horizon line offshore; such power plants have minimal impact on the environment and are more socially acceptable than onshore wind farms. It also increases dramatically the wind potential of coastal regions, albeit at a higher capital cost.

Offshore wind farms have thus become a viable option to replace or complement fossil fuel generation and onshore wind installations. Presently, the largest of these wind farms in service is the London Array, with 630 MW of installed capacity and with an eventual maximum capacity of 1 GW [8]. The integration of such a wind farm on any AC grid is a challenge because of the intermittent nature of wind energy.

To maximize the use of a link between an offshore wind farm collector substation and a onshore substation, one has to ask if integrating these two functions into one transmission system is possible. Such a system would serve two purposes; transmit power from one onshore point to another while collecting the electricity generated by an offshore wind farm. Therefore, multi-terminal DC networks can fulfill many roles [9] [10] [11] [12]:

- Integrate offshore wind power ;
- Integrate remote loads that are currently powered by fossil fuels ;
- Interconnect other onshore systems.

This is why we believe that multi-terminal DC systems can be interesting for transmission system owners in the near future.

1.2 *Integrating renewable generation through a multi-terminal DC network*

This thesis presents a method to evaluate the economic viability of a multi-terminal DC transmission grid that would integrate both sizable offshore renewable energy sources and remote load while interconnecting onshore systems. Such a grid can help integrating more renewable energy by granting access to offshore windfarms, removing the need for diesel power plants that serve small island communities and increase load diversity.

We chose to study DC systems instead of an AC systems because of the advantages of DC for submarine networks. DC transmission is more suitable than AC transmission for submarine networks [13] essentially because long AC cables suffer from a strong capacitive effect which causes the voltage to rise and requires expensive reactive compensation. Most HVDC projects are point-to-point transmission, but the multi-terminal DC system used here is inspired from the one presented in [14] by Veilleux and Ooi.

This thesis aims to refine and to build on the work of Jaffar [15] and of Baloch [16] who submitted dissertations on the subject of the planning of a marine transmission grid for the North Sea. They modeled a DC grid that could integrate offshore wind farms while interconnecting onshore grids subject to economical and geographical constraints, but without accounting for power flow constraints. Their work corresponds to what is described in this thesis in Section 3.3.1 (the planning problem).

Both of them used Mixed Integer Linear Programming (MILP) optimization techniques to maximize profit while planning a DC grid in the North Sea. MILP forces them to use an approximation to linearize the power flow equations. The model presented here is using Mixed Integer Non Linear Programming (MILNP) to have a higher fidelity representation of flows. This is further explained in the methodology chapter, specifically in Section 3.3.2 (operational problem).

1.3 Motivation for this thesis

The motivation for this thesis lies in the new options to generate and transmit electricity given by offshore wind farms and recent advances in HVDC technology. These advances allow relatively simple multi-terminal operation and make the integration of an interconnection and of offshore wind farms possible [15]. One important concern about renewable electricity generation is its maximum penetration because of the intermittent and uncertain nature of the renewable energy sources such as the wind and the solar irradiance. Maximum penetration of renewable energy sources is a function of:

- the balancing capability of the system (its ability to modulate generation to serve a varying load less non-dispatchable renewables) ;
- the sensitivity of the system operation to the variations in renewable generation.

A system that interconnects two grids while integrating wind farms will be able to integrate a greater wind generation capacity than a system with no interconnection since the larger load and generation diversity of the new interconnected system should permit a smoother integration of more intermittent resources.

Moreover, adding such interconnections can expand the geographical areas where networks can integrate wind power, which can also increase the diversity of the load served by the wind farms. Likewise, very often the peak demand occurs at different moments in different power grids. Therefore, it is not uncommon to see the peak demand of a larger interconnected network formed by two or more AC grids to be smaller than the sum of the peaks of the individual AC grids—Quebec and New York being a prime example. By reducing the peak demand of the whole region served by the two interconnected grids, one reduces the generating capacity needed, renewable or not, to serve the peak load.

The Maritime Link, a 500 MW HVDC submarine link between Newfoundland and Nova Scotia, is currently operating and could be part of a Gulf of St. Lawrence DC grid [5]. Hydro-Québec is also planning to build a submarine link to bring hydroelectricity to the Magdalen Islands by 2025 [7]. These projects motivated us to test the model with realistic data describing the Gulf of St. Lawrence region because they could be part of a future DC grid. This type of project can also help achieve two goals at the same time – the integration of far-flung parts of the Hydro-Québec network and generation resources in the middle of the sea while interconnecting several mainland networks.

We aim to help network planners to work with a new way of transmitting bulk power: a submarine DC grid that can integrate offshore wind generation. Traditional HVDC systems usually consist of only point-to-point electricity transmission and do not allow connecting multiple branches on a single node. In this thesis, we build a model that designs a large-scale DC grid and compute power flow for given parameters. To find a solution efficiently so that network planners can use the model on an everyday basis, we split the problem in two parts: the design of the DC grid and the actual power flow computation of the DC grid.

In this thesis we develop an approach to carry out the design of such DC grids according to the power that is available at each pre-established node. By feeding the design procedure with power (injected and extracted at each node) and capital costs that relate to voltage levels and cable size, power system planners and investors will get precise power loss values and true power flow. This will help them design the system to choose the right equipment for the project instead of relying only on manufacturer tables that simply link a power level with a voltage level and a cable size.

This thesis proceeds as follows:

- Chapter 1 gave the background information and explains why this is a worthy line of investigation
- Chapter 2 explains the design approach assumptions and their justifications
- Chapter 3 formulates the problem according to choices made in Chapter 2 and provides the heuristic solution technique needed to solve its underlying optimization problem as fast as possible

- Chapter 4 studies multiple cases using the design approach to show what it can do for planners
- Chapter 5 explores the possibility of making economic analysis with the model.

DC grids are more and more relevant for large-scale power transmission projects; we hope this thesis can contribute to the recent advances regarding their development.

2 METHODOLOGY AND ASSUMPTIONS

The goal of the present work is to build a mathematical programming model for planning an interconnection between potential multiple onshore nodes in existing power networks and potential multiple offshore wind farms. This system requires undersea cables, onshore substations and optional offshore substations.

In this chapter, we provide the necessary background for understanding the current state of technology regarding submarine HVDC transmission systems and offshore wind generation. This includes descriptions of the technologies considered and presented in this thesis. Before starting the development of the grid planning model (constraints, objective function and so on), it is necessary to settle the power transmission technology that should be used for the expected multi-terminal subsea grid systems.

2.1 Voltage Source Converter (VSC) HVDC

As stated earlier, one can build a high voltage grid using three different technologies. Given the context of a subsea system with distances beyond 50 km, one should dismiss the AC option. An AC high voltage grid would certainly be cheaper than a DC system, since it would not require any converter station by connecting directly to the main AC grids. However, for underground or undersea cables, AC systems have great limitations. AC cables induce large capacitive effects that limit their length. Losses in long AC cables (more than 30-40 km) are also greater than in DC cables of similar length [17]. High Voltage and Ultra High Voltage overhead lines compete with DC technologies for transmitting large amounts of power on very long distances over land, but when it comes to undersea or underground high voltage cables, AC options are no match for DC.

Two DC technologies are competing with each other: Line-Commutated Converter (LCC) HVDC (based on thyristors) and Voltage-Source Converter (VSC) HVDC (based on Insulated-Gate Bipolar Transistors - IGBT). The authors of [15] state clearly that VSC HVDC is better for a multi-terminal system, and [17] affirms that the connection of offshore wind farms is virtually impossible when using LCC HVDC. This is because thyristors can be only triggered into the on-state by applying a pulse of positive gate current, while IGBTs can be turned on and off and operate in a time on the order of 1µs [18]. Thus, thyristors need an AC waveform to start operating, thus usually preventing operation in a dead grid. VSC systems can provide an AC voltage waveform from their DC side, thus are black start capable [19]. Black start capability is very useful if the DC grid integrates isolated offshore windfarms or small autonomous AC grids. VSC systems are thus more flexible than LCC systems and more appropriate to connect isolated elements. Here is a list of the main characteristics of both LCC and VSC converters:

LCC systems [20]:

+ operate with relatively low power losses (1-2 %).
– do not allow black starts. They can only transfer power between two (or more) active grids. An auxiliary start-up system would be necessary for an offshore node.
– cause high harmonic distortion because their firing angle control causes sharp commutations of the AC-side line currents. LCC systems thus need complex filtering systems on all ends that interconnect with the AC systems.
– can only control active power. What is more, the AC-side currents being out of phase with the line voltages, substantial reactive power compensation is required.
– need large areas to install converters.

In comparison, VSC systems [20]:

+ allow black starts. No auxiliary start-up system is necessary.
+ commute at high frequency (1-2 kHz) which reduces harmonic distortion. All filters in a VSC system are smaller than the equivalent LCC components.
+ control active and reactive power. No reactive power compensation is needed on AC sides.
+ need smaller areas to install converters.
+ allow connection to weak AC grids.
– operate with relatively high power losses (4-5 %).

For these reasons, we believe that VSC HVDC is the most appropriate technology for the multi-terminal systems considered here to interconnect onshore and offshore nodes. Figure 2 illustrates a typical topology to interface an AC grid with a DC grid for a VSC-HVDC installation.

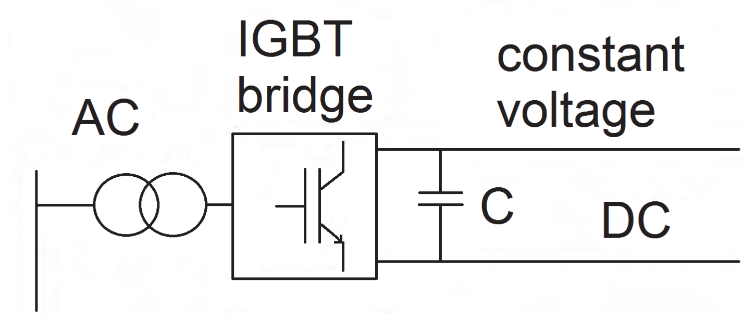

Figure 2 – A VSC HVDC terminal that interconnects a DC grid with an AC grid [17]

2.2 Cross-linked polyethylene insulated (XLPE) Cables

Prior to 1990, high voltage (more than 69 kV AC) power cables installed in Québec and many other locations worldwide were insulated with oil. This type of insulation limits the length of cables by imposing fluid pressure feeding. Moreover, especially for submarine links, oil leaks could lead to important environmental damage and cable malfunction. Recently, promoters have considered two types of cables to build long DC submarine transmission links: Mass-Impregnated (MI) cables and cross-linked polyethylene insulated (XLPE) cables. Mass impregnated cables still prove to be the most suitable solutions for bulk power transmission because they can work at up to 600 kV DC [21], but XLPE have the advantage of being lighter and easier to handle. Hydro-Québec TransÉnergie (HQT) is currently planning to install XLPE cables for two new DC lines interconnecting the HQT network asynchronously with the neighbouring Eastern Interconnection:

- Québec - New Hampshire Interconnection (Northern Pass Project on the US side): HQT plans to install XLPE underground cables under the Hereford forest
- Hertel – New York Interconnection (Champlain Hudson Power Express project on the US side): HQT plans to install underground and submarine XLPE cables.

When replacing the existing AC oil-insulated cables located in downtown Montréal, HQT now installs XLPE cables that are simpler to maintain since no oil pumping system is required.

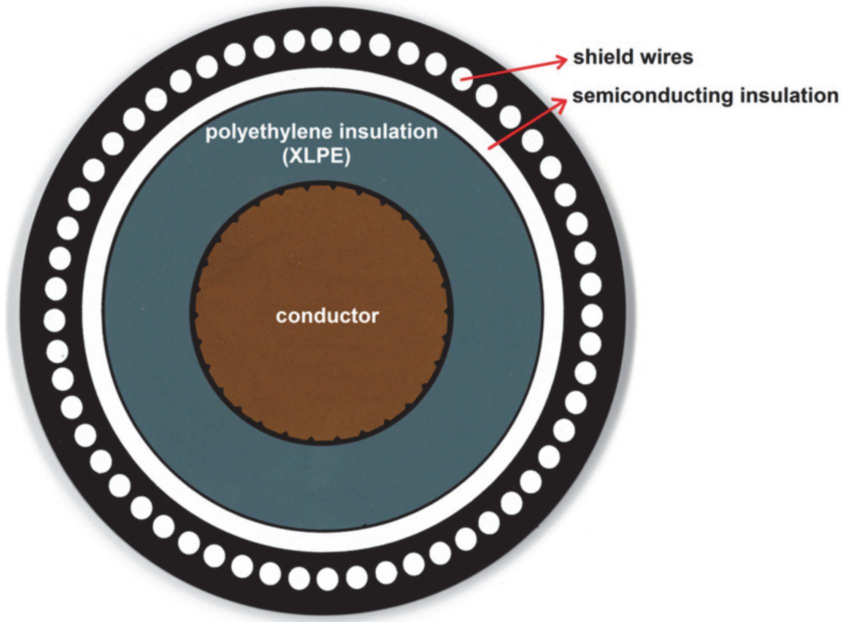

Figure 3 – XLPE cable cross-section (from an ABB cable cross section mock-up)

Recent projects have shown that HVDC links can carry 500 MW per cable. The INELFE (INterconnexion ELectrique France-Espagne) project comprises a ± 320 kV XLPE HVDC underground cable which includes two 1,000 MW bipolar circuits for a total power rating of 2 GW [22]. This project inspired us to use this technology as a benchmark for the model presented in his thesis.

Recent developments announced by cable manufacturer NKT in XLPE cables have shown that a 640 kV DC, 3 GW XLPE cable is on its way [23]. Despite its availability, developers have been reticent to use it. For example, manufacturers Nexans and Prysmian delivered two 393 km MI cables for the recent project aiming to interconnect Montenegro and Italy (Mon.ITA project). These cables are rated at 500 kV DC and transmit 500 MW each [24]. Manufacturers are developing more and more XLPE cables with higher voltage ratings than 320 kV, but project promoters still install MI submarine cables when a DC voltage higher than 320 kV is required.

2.3 *Offshore windfarms*

Wind farms harness an energy that is both clean and relatively inexpensive, but land-based wind farms require large areas and may be undesirable to the local population because of visual and noise impacts. Therefore, since 2009, promoters have built large offshore wind farms to generate wind power while minimizing their social and visual impacts. Table 1 provides a list of large offshore wind farms built since 2009. As far as we know, those are the ten largest built offshore windfarms at the time of writing.

Wind farm	Capacity (MW)	Location	In-service date	Source
London Array	630	United Kingdom	2012	[8]
Gemini Wind Farm	600	Netherlands	2017	[25]
Gode Wind I & II	582	Germany	2017	[26] - [27]
Gwynt y Môr	576	United Kingdom	2015	[28]
Greater Gabbard	500	United Kingdom	2013	[29]
Dudgeon	402	United Kingdom	2017	[30]
Veja Mate	402	Germany	2017	[31]
Anholt	400	Denmark	2012	[32]
BARD Offshore 1	400	Germany	2013	[33]
Global Tech I	400	Germany	2015	[34]

Table 1 – List of offshore wind farms of at least 400 MW

Offshore wind farms are a recent trend and their number will continue to grow. As of June 2017, in the United Kingdom alone, the total installed capacity of offshore windfarms was 5.36 GW. Promoters are planning for more than 13 GW of new capacity by 2025, and 2.97 GW is already under construction [35]. Nearer to Québec, the state of Massachusetts launched a request for proposal (83C) for 400 to 800 MW of offshore wind energy generation on December 20, 2017 and awarded it to an 800 MW project on May 23rd, 2018 [4]. The state aims to develop 1600 MW of offshore windfarms by June 30, 2027 [36]. These numerous projects have inspired us to include the integration of offshore wind generation in the approach presented in this thesis.

2.4 Model characteristics

For the purpose of this thesis, the VSC HVDC model needs to fulfill both of these roles: an interconnection between onshore nodes of a power system and the potential integration of offshore wind farms. For the model to be useful, it must include the following parameters:

- For onshore terminals:
  - maximum injecting power
  - electricity demand
  - price of energy
- For offshore terminals:
  - maximum injecting wind power
  - price of energy (cost of wind generation)
- For DC links (representing DC undersea cables):
  - fixed cost
  - variable cost
  - maximum capacity
  - resistance per unit length

The goal of the design approach is to provide a solution that minimizes total cost while fulfilling its power system mission over the life of the equipment and keeping the computational burden light for large-scale systems. Cost components include link cost (variable and fixed) and proxy generation costs at each node of the system. The constraints are the power flow equations, the power balance, the capacity of the cables, the maximum and minimum voltage levels and the maximum power injection / extraction at each node.

2.5 Design variables

For the purpose of this thesis, the VSC HVDC model needs to fulfill both of these roles: an interconnection between onshore nodes and the potential integration of offshore wind farms. The main design variables are the following:

- For onshore terminals:
  - injecting power
- For offshore terminals:
  - injecting wind power
- For DC links (representing DC undersea cables):
  - link occurrence
  - link capacity

These variables must allow the designer to choose DC links and optimize a power flow solution. The next chapter formulates the optimization problem.

3 OPTIMIZATION PROBLEM FORMULATION

Now that the requirements for the model are set, the mathematical equations representing the objective function and the constraints can be set. Throughout this section, every constraint of the model will be analyzed. We describe the mathematical tools that will be used to solve the corresponding mathematical optimization problems.

3.1 Optimization problem

This section describes the parameters, the variables and the constraints that describe the complete optimization problem. The main constraint of the operations problem is the power flow equation accounting for the cable resistances, thus power losses and true physical flow split between parallel paths of different impedances.

3.1.1 Parameters

The model contains M possible nodes (N_1 to N_M). Indices n and m each run from N_1 to N_M. Links can go from any node $n \in M$ to any other node $m \in M$ where $n \neq m$. The demand and available generation are set for each node. The goal of the optimization process is to balance supply and demand at each node while minimizing the cost of generation and the cost of links.

The parameters are the following:

- $d(n)$ – power demand (extraction) at node *n* (in MW)
- $Dist(n, m)$ – table of distance between each node pair (in km)
- $fixcost$ – fixed cost of a link in $/km
- $fmax$ – maximum flow of largest cable available
- $gmax(n)$ – maximum power injection at node *n* (in MW)
- $price(n)$ – price of power at node *n* in $/MW
- $R(n, m)$ – table of link resistances between each node pair (in pu/km)
- $varcost$ – variable cost associated with flow (in $ · km/MW)
- $vmax$ – maximum voltage (in pu)

3.1.2 Variables

The variables (each representing degrees of freedom) are listed here:

- $f(n,m)$ – power flow between nodes *n* and *m* (in MW)
- $g(n)$ – net power injection at node *n* (in MW)
- $v(n)$ – voltage at node *n* (in p.u.)
- $u(n,m)$ – matrix of link occurrence (1 or 0 at each position)

The matrix $u(n,m)$ is symmetric and has a zero diagonal by definition, so there are only $\frac{n(n-1)}{2}$ variables. For example, this matrix represents a four node system with two possible links (N_1, N_2) and (N_2, N_3):

$$u(n,m) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \Rightarrow$$

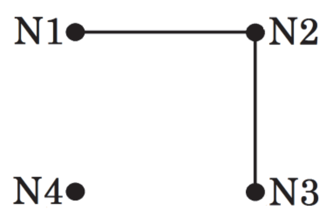

Figure 4 – Table of link occurrence example

Values of 1 in the (1, *j*) position of the matrix indicate the presence of a link between nodes 1 and *j*. Here the (1, 2) and (2, 1) values in the matrix represent the presence of a link in the N_1-N_2 position while the (2, 3) and (3, 2) values represent the presence of a link in the N_2-N_3 position.

3.1.3 Objective function

The objective function represents the total cost. The objective is to minimize the total cost, which is the sum of the cost of generating/purchasing power and the total cost of ownership of the links over the same period of time. The costs of the cables are assumed to be dependent on both the flow capacity in each cable and a fixed component. The total cost can be broken down:

$$Total\ cost = Cost\ of\ power\ injections + Cost\ of\ links \qquad (3\text{-}1)$$

where

$$Cost\,of\,power\,injections \;=\; price(n)\cdot g(n) \tag{3-2}$$

and

$$Cost\,of\,links = \sum_{all\,links} (Dist(n,m)\cdot(fixcost\cdot u(n,m)+varcost\cdot|f(n,m)|))$$

(3-3)

3.1.4 Power flow and power balance

The power flow equation originates from Ohm's law for a DC circuit. Rearranging

$$P_{flow\,from\,A\,to\,B} = V_A \cdot I_{A\,to\,B} \tag{3-4}$$

and

$$I_{A\ to\ B} = \frac{V_A - V_B}{R_{link\ from\ A\ to\ B}} \tag{3-5}$$

gives

$$P_{flow\ from\ A\ to\ B} = V_A \frac{V_A - V_B}{R_{link\ from\ A\ to\ B}} \tag{3-6}$$

Applied on our model, the power flow equation is the following:

$$f(n,m) = \frac{v(n)\cdot(v(n)-v(m))}{R(n,m)} \tag{3-7}$$

which is the equality needed to compute the power flow in the branches of the grid. The power flow constraint does not apply on branches that are not built. One can see that this equation is not linear with respect to the variable $v(n)$; this is the reason why the problem is non-linear. Moreover, the products $v(n)\ v(m)$ are known to be non-convex as well.

The power balance constraint makes sure that the power injections are equal to the power extractions for each node. It is the following for each node $n \in M$:

$$g(n) - d(n) + \sum_{m=1}^{M} u(n,m) \frac{v(n) \cdot (v(n) - v(m))}{R(n,m)} = 0 \qquad (3\text{-}8)$$

3.1.5 Sizing constraints

A few other constraints must be in place for the optimization problem. The following variables are subject to a maximum and/or a minimum set by parameters:

- Injection at each node:

$$0 \leq g(n) \leq gmax(n) \qquad (3\text{-}9)$$

- Power flow through each branch:

$$|f(n,m)| \leq u(n,m) \cdot fmax \qquad (3\text{-}10)$$

- Voltage at each node:

$$|v(n)| \leq vmax \qquad (3\text{-}11)$$

Here is an overview of the operations problem, where z is the total cost defined at equation (3-1):

$$\min_{g,u,f,v} \; z(g,u,f,v)$$

$$\begin{aligned}
&\text{s.t.} \\
&0 \leq g(n) \leq gmax(n) \quad \forall \{n\} \\
&|f(n,m)| \cdot u(n,m) \leq fmax \quad \forall \{n,m\} \\
&|v(n)| \leq vmax \quad \forall \{n\} \\
&g(n) - d(n) + \sum_{m=1}^{M} u(n,m) \frac{v(n) \cdot (v(n) - v(m))}{R(n,m)} = 0 \quad \forall \{n\} \\
&u(n,m) \in \{0,1\}
\end{aligned}$$

The optimization problem is stated. Two elements in particular make it hard to solve. The incidence matrix of links is to be filled by integers and the power flow constraints are non-linear. This is thus a MINLP problem. As we explain next, we suggest to split the problem to alleviate this complication.

3.2 The difficulty of designing a DC grid and solving for a power flow solution in a single model

Since the method must both design a DC grid and test the power flow with the provided parameters to provide a solution, it must solve a mixed-integer non-linear programming (MINLP) optimisation problem. The network design part is a mixed-integer problem (DC links exists or do not exist) and the power flow part is non-linear in the voltage magnitudes (see eq. 3-7 in Section 3.1.4).

As stated in Section 2.4, we want to keep the computational burden very light and to use readily available tools so that the model is practical for network planners. To do so, we develop a heuristic technique that splits the problem into two parts:

- A network designing step (planning approach) that outputs a DC grid (connectivity and link sizing) using mixed-integer linear programming (MILP)
- A power flow evaluation step (operations approach) that verifies the solution's feasibility and that computes precise power flow and power losses using non-linear programming (NLP).

Splitting the problem in two parts allows us to make use of powerful commercial MILP and NLP solvers without much complications. We acknowledge that the solutions found here may not be globally optimal. However, the goal of our approach is to provide planners with good initial solutions which could be refined with more specific local searches and adjustments. We suggest the development of a unique MINLP solver for power flow problems in Section 6.1.4.

3.3 The Planning problem and its solution using a conventional planning approach vs using an operations approach

Planning a power system is an optimization problem. It consists of building a grid between generators and customers while minimizing costs to serve load at all times with a pre-defined level of reliability. In the case of the DC submarine grid considered here, it consists of choosing what link to build and sizing the links. In general, the optimal power flow problem is a non-linear programming (NLP) problem with the goal of minimizing the total cost of meeting demand [37]. As explained in Section 3.2, the model that we need to solve here requires the optimization of the decision to build or not to build DC links.

Since one can estimate the optimal power flow with MILP [38], we propose to simplify it by replacing it with a transportation problem that will output a network configuration and capacity. Less complicated than a power flow problem, it is linear and we can solve it using MILP. Electrically-speaking this is equivalent to relaxing Kirchhoff's Voltage Law (KVL), while keeping Kirchhoff's Current Law (KCL).

To model accurately a DC grid with parallel paths between nodes, we then put this configuration to an operation-like problem (which considers both the effects of KVL and KCL) in an NLP problem that takes into account losses, voltage drops and the full power flow equations. Solving these two problems requires reasonable computing time and allows finding a precise solution to the optimal power flow of the configuration given by the planning problem.

3.3.1 Planning problem formulation via a "transportation" tool - Mixed Integer Linear Programming (MILP)

The first MILP step to solve the problem is to determine an incidence matrix that indicates which links must be built to meet supply and demand constraints. Even by relaxing the power flow equations, replacing them with simplified power balance equations, the optimization of the grid results in a minimal number of links to balance supply and demand at minimum capital cost. Section 3.3.4 formulates this transportation problem.

3.3.2 Planning problem formulation via an "operational" tool - Non Linear Programming (NLP)

In general, the optimal power flow problem is a large-scale nonconvex NLP problem [39]. By removing the link choice portion from the optimal power flow problem, we are able to solve an optimal power flow for a given network topology.

Solving complex optimal power flow problems is relevant for studying many new technologies including smart microgrids [40] and large-scale storage integration. [41] Solving these problems aims at minimizing losses, minimizing the cost of generation or optimizing the use of storage devices.

3.3.3 Split of the optimal planning problem

As seen in chapter 2, the optimal power flow problem is split in two simpler problems. To formulate both optimization problems, we must determine which constraints fall in the planning portion and which in the operations portion.

Being naturally linear, the planning model deals with the power balance constraint and outputs a link occurrence matrix. This matrix is kept fixed and fed to the nonlinear operations model that deals with an additional constraint, the power flow constraint, and outputs the final power flow solution.

3.3.4 Connectivity: Transportation problem

This section describes the parameters, the variables and the constraints that are used to solve the simplified network-flow planning problem. It consists of minimizing the cost to meet the power demand at all nodes while considering multiple constraints. Its purpose is to choose what links will be built. The main constraint of the planning problem is the power balance. It states that for each node, the sum of the power flows and the power extraction/injection is zero. The other constraints in this problem are sizing constraints describing the available generation at each node and the maximum cable capacity.

3.3.5 Objective function

The objective function represents the total cost. The objective function of the operations problem is identical to the objective function of the complete problem (section 3.1.3). The objective is, again, to minimize the total cost which is the sum of the cost of generating power and the cost of building the links.

3.3.6 Power balance constraint

The power balance constraint makes sure that the power injections are equal to the power extractions for each node. It must be kept in the transportation problem. It is the following for each node:

$$g(n) - d(n) + \sum_{m=1}^{M} f(n,m) = 0 \tag{3-12}$$

Note here the absence of the non-linear power flow constraint to keep the problem linear. Line flow proxies $f(n, m)$ take that role.

3.3.7 Sizing constraints

A few other constraints must be in place for the optimization problem. The following variables are subject to a maximum and/or a minimum set by parameters:

- Injection at each node:

$$0 \leq g(n) \leq gmax(n) \tag{3-13}$$

- Power flow through each branch:

$$|f(n,m)| \leq u(n,m) \cdot fmax \tag{3-14}$$

This problem does not take into account the power flow relationships as constraints; hence there are no voltage variables to consider; in effect this is a pure transportation problem and not an optimal power flow. Here is an overview of the planning problem, where z is the total cost defined at equation (3-1):

$$
\begin{aligned}
&\min_{g,u,f} \; z(g,u,f) \\
&\text{s.t.} \\
&0 \le g(n) \le gmax(n) \;\; \forall \{n\} \\
&|f(n,m)| \cdot u(n,m) \le fmax \;\; \forall \{n,m\} \\
&g(n) - d(n) + \sum_{m=1}^{M} f(n,m) = 0 \;\; \forall \{n\} \\
&u(n,m) \in \{0,1\}
\end{aligned}
$$

The planning problem is stated.

3.4 Solution quality assessment: Operations problem

This section describes the parameters, the variables and the constraints that are used to solve the operations problem. The main constraint of the operations problem is the power flow equation accounting for the cable resistances, thus power losses and true physical flow split between parallel paths of different impedances.

3.4.1 Objective function

The objective function represents the total cost. The objective function of the operations problem is similar to the objective function of the complete problem (section 3.1.3), this time considering *u(n,m)* as input (output of the transportation problem). The objective is, again, to minimize the total cost which is the sum of the cost of generating power and the cost of building the links.

3.4.2 Sizing constraints

The sizing constraints of the operations problem are already listed in section 3.1.5. They are the same than for the complete problem. Here is an overview of the operations problem, where z is the total cost defined at equation (3-1):

$$
\begin{aligned}
&\min_{g,f,v} \ z(g,f,v) \\
&\text{s.t.} \\
&0 \leq g(n) \leq gmax(n) \ \ \forall \{n\} \\
&|f(n,m)| \cdot \widehat{u}(n,m) \leq fmax \ \ \forall \{n,m\} \\
&|v(n)| \leq vmax \ \ \forall \{n\} \\
&g(n) - d(n) + \sum_{m=1}^{M} \widehat{u}(n,m) \frac{v(n) \cdot (v(n) - v(m))}{R(n,m)} = 0 \ \ \forall \{n\}
\end{aligned}
$$

Now that the optimization problem is stated, the model must be validated in Chapter 4.

3.5 Operations problem relaxation

Experimenting, we found out that the operations problem, being more constrained than the planning problem, is for some cases infeasible. The main parameter that influences this feasibility is the maximum cable capacity. Therefore, while building a solution for each case, relaxing the problem by adding flexibility (increase cable capacity or add generation flexibility) between solving the two problems often helped to solve the operations problems. We observe that the more complex the power flow problem is, the more we need to increase this differential capacity. Figure 5 shows the process used to build solutions with our model.

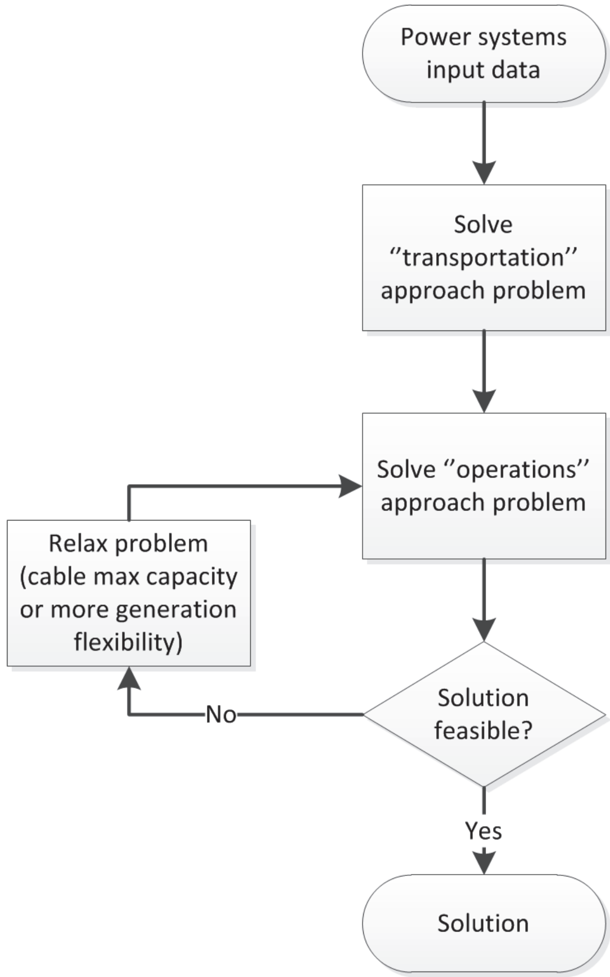

Figure 5 - Optimization flow chart

4 CASE STUDIES

The previous chapters developed a method to design the HVDC interconnection between on- and off-shore nodes. This chapter makes use of the design approach in a case with given geographical coordinates and market data to test its optimization capabilities and its limitations.

4.1 Candidate networks and model characteristics

To test the model, we need a set of links and nodes to optimize. Section 1.3 explained why we chose the Gulf of St. Lawrence. Figure 6 shows where the Gulf of St. Lawrence is situated in North America.

Figure 6 – Location of the Gulf of St. Lawrence in North America – background map: Retrieved from Google Earth [42]

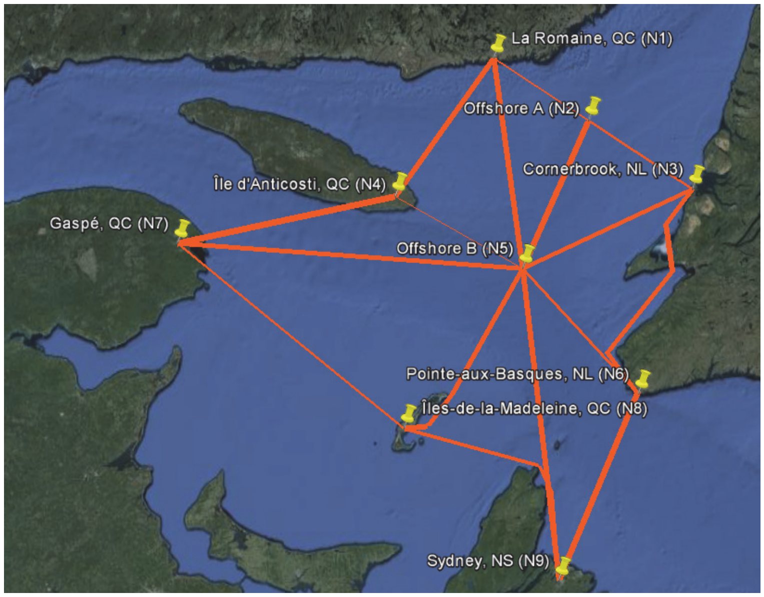

Figure 7 - Large-scale DC system with 9 possible nodes (N1 to N9) – background map: Retrieved from Google Earth [42]

The model contains nine possible nodes (N1 to N9) as shown at Figure 7 for a maximum of seven onshore nodes, two offshore nodes and sixteen possible links. The nine nodes represent various geographical locations in the Gulf of St. Lawrence. The case study considers a system that can interconnect the Canadian provinces of Québec, Newfoundland and Labrador and Nova Scotia. We study multiple cases varying parameters, such as the price of electricity, the available generation and the power demand at each node. The task is to compare different scenarios of partial or complete connections between these nodes in different economic conditions to validate the model.

4.2 Case study: Gulf of St. Lawrence

We can implement the mathematical model we have from Chapter 3 by mapping the nodes on an x - y coordinate grid representing a real-world geographical area. With the computational power and the solution algorithms available, we experienced that a 3x3 grid with coordinates on the x and y axes shows the complexity needed to test the model and is small enough so that algorithms can deal with it in a reasonable computation time. A larger grid would mean way more complexity and a smaller grid would not be a very big optimization challenge. The bottom line is that the coordinate grid needs to be sized in order to capture the locations of potential interconnection points with sufficient accuracy.

For testing the approach adopted in this thesis, the case of a submarine DC grid in the Gulf of St. Lawrence was chosen for the following main reasons:

- The Gulf problem can be described accurately enough with a 3 by 3 grid
- Newfoundland and Nova Scotia power systems are already interconnected through a DC cable [5]
- Hydro-Québec will link the Magdalen Islands' system with the main Québec system in 2025 [7]
- The distances (80 to 300 km) between each node correspond to feasible DC marine cable lengths.

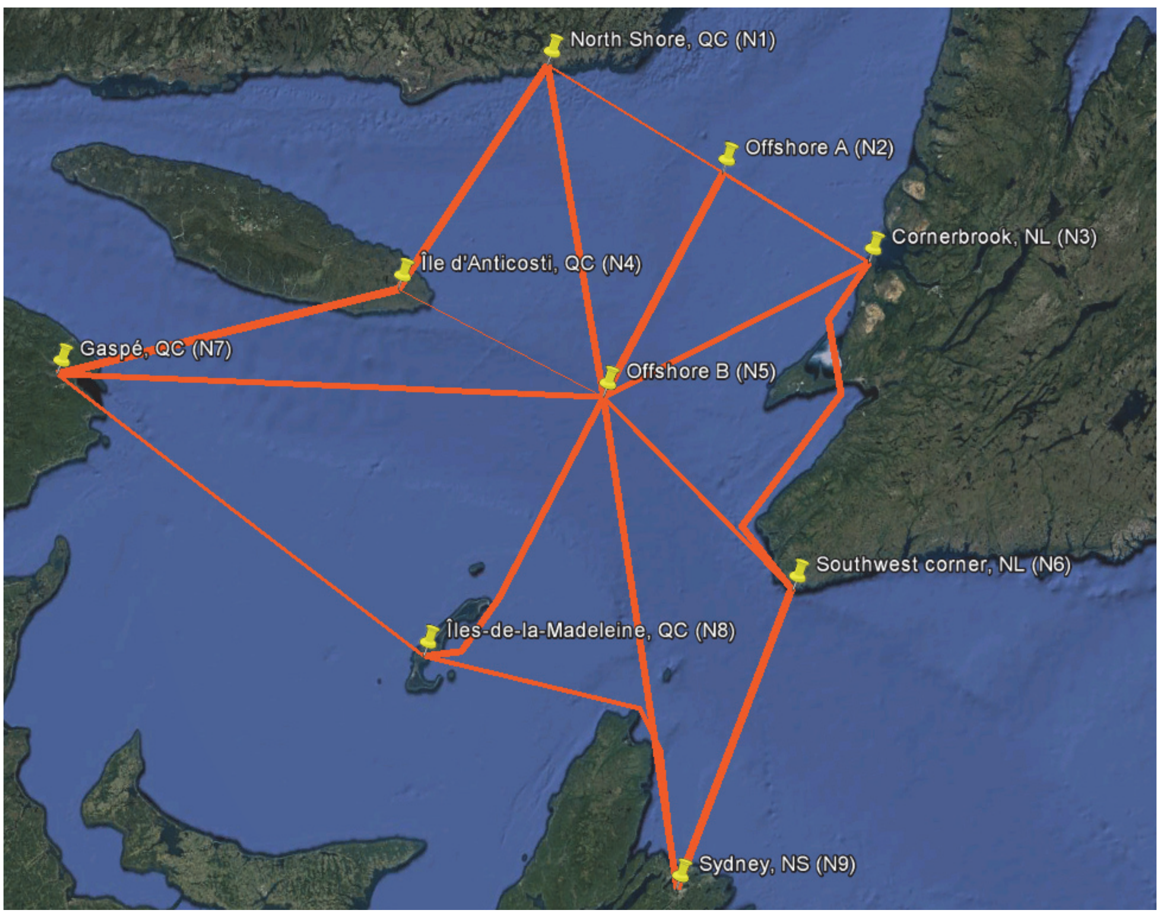

Figure 8 - Model Overview – background map: Retrieved from Google Earth [42]

Figure 8 shows the Gulf St. Lawrence, its nodes and the maximum number of links and stations that the test configuration allows. This system could contribute to the decarbonisation of other power systems by transmitting clean hydroelectric or wind power to systems where the main source of energy is fossil fuels.

To describe the environment in which this system can be built, we need to provide the following parameters:

- Amount of power available for injection/extraction in the DC grid at all nodes
- Demand in power at each node
- Price of power at each node
- Geographical configuration of the potential grid
- Cable resistance
- Cable per unit length cost

We are not optimizing with respect to the grid rated voltage; we assume it to be given here. The cost of converters is also not included because their cost depends on the onshore grids they are connected to. We suggest building a cable size and voltage level optimizer as further research in section 6.1.1.

The 3x3 configuration used in the model makes sense from a geographical point of view for the Gulf of St. Lawrence and the power systems of the region. This configuration is also useful for the planner to enforce the N-1 transmission planning criterion since even when a cable is unavailable for scheduled maintenance or because of a fault, each terminal can be connected to the others through at least another path. Table 2 shows the potential links and their respective lengths.

(km)	N1	N2	N3	N4	N5	N6	N7	N8	N9
N1		112	-	143	175	-	-	-	-
N2			89	-	140	-	-	-	-
N3				-	161	196	-	-	-
N4					120	-	194	-	-
N5						147	288	177	269
N6							-	-	170
N7								241	-
N8									218
N9									

Table 2 – Potential links available to the planning problem and their lengths in km

In this Chapter, every case assumes a 320 kV DC system with a cable resistance of 0.012 ohms/km, which corresponds approximately to a 1500 mm^2 submarine cable [43]. In Chapter 5, we will explore the possibility of optimizing the voltage level and the cable size.

4.3 Implementation in multiple conditions

To validate the model, we decided to test it in multiple realistic conditions. For each case, each link is on the table. The CPLEX solver (MILP) can build any link to meet demand, as in a transportation problem. In the second problem, the KNITRO solver (NLP) finds an optimal solution to the power flow equations given the links to work with. With the second problem output, the planner can take an informed decision knowing the power losses, the voltage drop and the power flow for each cable.

4.3.1 Case 1: Cable to connect the Magdalen Islands (QC)

Hydro-Québec (HQ) currently generates power using diesel motor-generator sets to deliver electricity to the Magdalen Islands (Node N8 shown in Figure 8). The peak power demand in the islands from 2013 to 2017 was 45.3 MW. Linking the islands with a submarine cable, as suggested in the most recent HQ strategic plan, would have clear environmental benefits by lowering the amount of fuel delivered to and burned in the diesel power plant.

Power delivered through a submarine cable could come from two sources in Québec: the north shore (Côte-Nord) of the Gulf of St. Lawrence, with its abundant hydroelectric power or Gaspésie, with wind power to share. Wind power being intermittent and considering the cost of reinforcing the HQ network, it may cost more since HQ would need to flow hydroelectric power from the North Shore (N1) by the land grid to balance the wind power delivered to the islands when the wind does not blow in Gaspésie. Therefore, one can set the power at N7 (Gaspésie region) to a higher price than power at N1 (North Shore region). We also see from Table 2 that the cable length from Gaspésie (N7-N8) to the islands is shorter than the cable length from North Shore (N1-N5 + N5-N8 or N1-N4 + N4-N8).

The approach minimizes the summation of the cost of generation and the cost of the link. Generation is available at N1 and N7; however, power is cheaper at N1 than at N7, but a link from N1 to N8 is longer and therefore more expensive than a link from N7. Table 3 summarizes the parameters for this study and its underlying design results.

Parameters (input)		Variables (Output - Results)	
Demand at N8 Price at N8	60 MW 12 $/MW	**Planning:** Link Gen at N7	 N7-N8 60 MW
		Objective value (maximum profit, revenue minus costs)[1]	44.5 $[1]
Generation cost N1 Generation cost N7	2 $/MW 7 $/MW	**Operations:** Gen at N1 Gen at N7	 0 MW 60.102 MW
Variable cost of link	1 k$/MW-km	Voltage at N7	1 pu (set)
Fixed cost of link	1 $/km	Voltage at N8	0.998 pu
		Losses in cables	0.102 MW (0.2%)
		Objective value (maximum profit, revenue minus costs) [1]	43.8 $[1]

Table 3 – Case 1 inputs and outputs

The cost difference in generation is not enough to build a link to N1. The planning model gives the following solution (N7-N8), shown in Figure 9.

[1] This value does not represent the result of a cost-benefit analysis. Parameters are defined to test the model in different conditions.

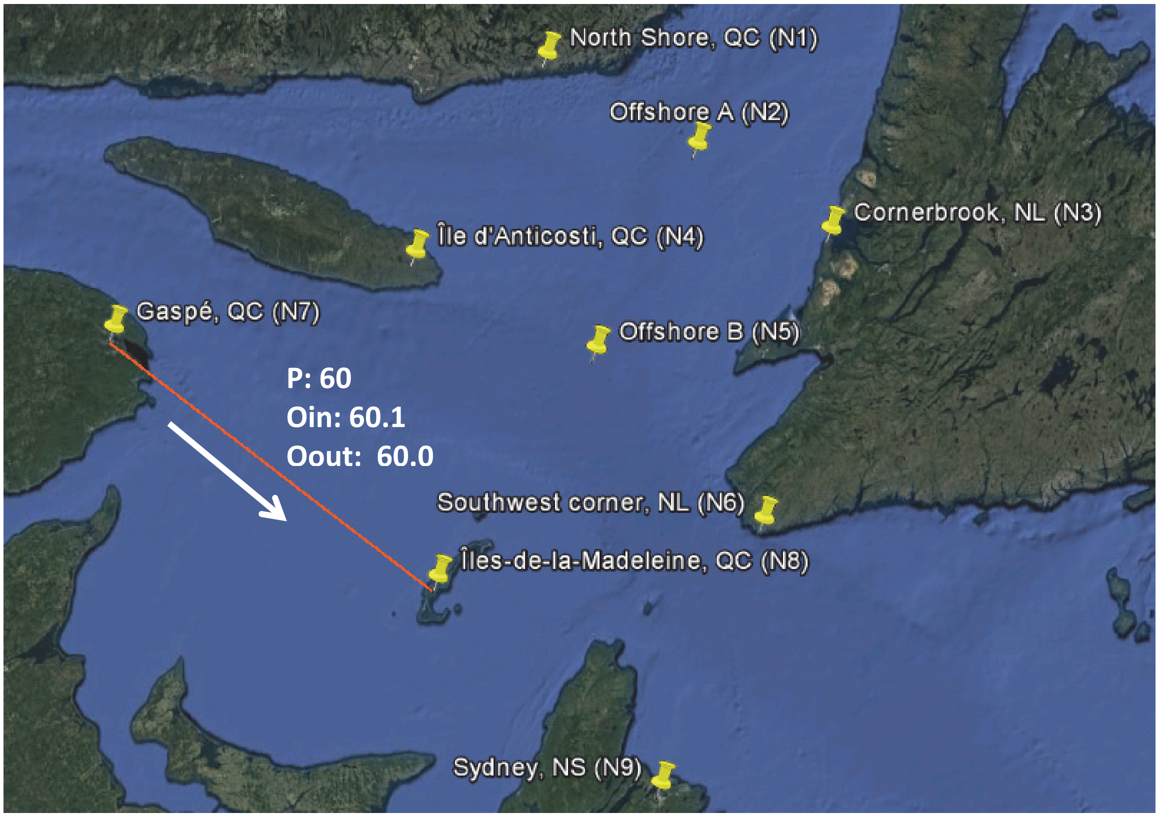

Figure 9 – Power flow in MW, Case 1 (P: Planning; O: Operations) – background map: Retrieved from Google Earth [42]

The solution to the planning problem is to build a cable to Gaspé (N7) since the supplemental cost of the cable to N1 is more than the supplemental cost of buying power at N7 instead of N1. The power loss level in the cable is very low (0.2%), implying that the planner could choose to reduce the voltage level to lower the costs of the converters at N7 and N8, as we will see in Section 5.1. The solution to this case implies that only one cable powers the islands, therefore providing no redundancy. The diesel motor-generator sets would probably need to provide backup power when the cable is not operating due to a fault or to maintenance.

4.3.2 Case 2: Interconnection between Newfoundland and Nova Scotia

Emera, in 2017, started to run the Maritime Link, a 200 kV HDVC link between Newfoundland and Nova Scotia [5]. This project inspired this case since it could be part of a

DC grid in the St. Lawrence. Emera plans to use the cable to export power from Labrador to the continent, but it also brings flexibility in the maritime provinces by opening the Newfoundland market to the other Northeast Power Coordinating Council (NPCC) members in the region.

We build this case by first setting a demand of 450 MW that the system must meet in Nova Scotia. Generation is mainly available in Newfoundland, but wind power is available at other nodes.

The approach minimizes the summation of the cost of generation and the cost of the link. Since only a single link to Newfoundland is enough to meet demand in Nova Scotia, the planning model builds a single link.

Parameters (input)		**Variables (Output - Results)**	
Demand at N9 Price at N8	450 MW 10 $/MW	**Planning:** Link Gen at N6	 N6-N9 450 MW
		Objective value (maximum profit, revenue minus costs)[2]	1553.5 $[2]
Gen at N2, N3, N4 and N5 Generation at N6	25 MW @ 5 $/MW for each node 500 MW @ 6 $/MW	**Operations:** Gen at N2, N3, N4 and N5 Gen at N6	 0 MW 454,1 MW
Variable cost of link	1 k$/MW-km	Voltage at N6	1 pu (set)
Fixed cost of link	1 $/km	Voltage at N9	0.991 pu
		Losses in cables	4,101 MW (0.9%)
		Objective value (maximum profit, revenue minus costs) [2]	1528.2 $[2]

Table 4 – Case 2 inputs and outputs

The cost difference in generation is not enough to build a wind collector in one of locations N2, N3, N4 and N5. The planning and operations models give the following solution illustrated in Figure 10.

[2] This value does not represent the result of a cost-benefit analysis. Parameters are defined to test the model in different conditions.

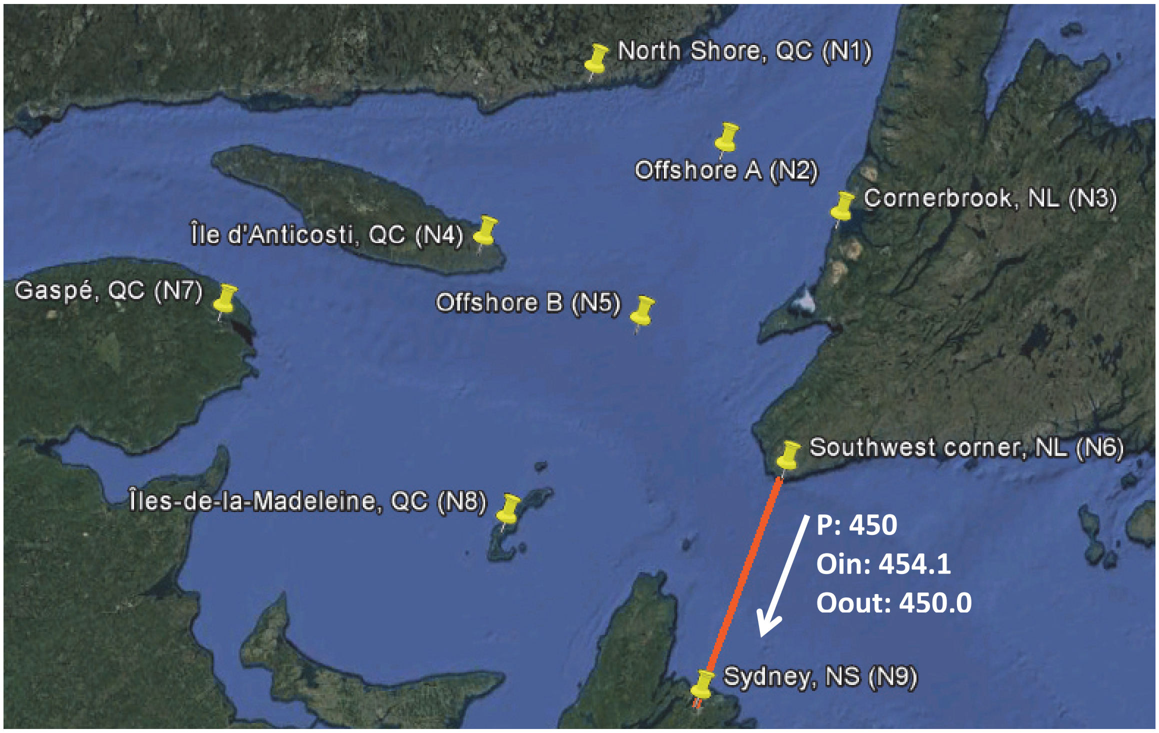

Figure 10 – Power flow in MW, Case 2 (P: Planning; O: Operations) – background map: Retrieved from Google Earth [42]

The solution to the planning problem is to build a single cable from Newfoundland to Nova Scotia since Newfoundland, in this case, can meet the demand in Nova Scotia. Wind power is less expensive, but the substantial cost of building links to collect wind power is larger than the gain of generating wind power over buying it in Newfoundland. The power loss level in the cable is 0.9%.

4.3.3 Case 3: Wind power collector

This case aims to build a DC grid to collect wind power to meet demand in Nova Scotia. In Section 2.3, we saw that multiple promoters both in North America and Europe are planning to build offshore wind generation. If such projects were to be built in the Gulf of St. Lawrence, a wind power collector system of some sort would need to be planned.

Demand in Nova Scotia is set to 350 MW of wind power, which is available offshore (N2 and N5), in Cornerbrook (N3), in Anticosti (N4), in Gaspé (N7) and in the Magdalen Islands (N8).

Parameters (input)		**Variables (Output - Results)**	
Demand at N9 Price at N9	450 MW 10 $/MW	**Planning:** Links Gen at N2 Gen at N3, N4, N5, N8	 N2-N3, N3-N5, N4-N5, N5-N8, N8-N9 50 MW 100 MW each
		Objective value (maximum profit, revenue minus costs)[3]	1284.4 $[3]
Gen at N2, N3, N4, N5, N7, N8	100 MW @ 5 $/MW for each node	**Operations:** Gen at N3, N4, N5, N8 Gen at N2 Gen at N7	 100 MW each 58.7 MW 0 MW
Variable cost of link	1 k$/MW*km	Voltage at N2 Voltage at N3 Voltage at N4 Voltage at N5 Voltage at N8 Voltage at N9	1.002 pu 1.002 pu 1.000 pu (set) 0.999 pu 0.991 pu 0.979 pu
Fixed cost of link	1 $/km		
		Losses in cables	8.7 MW (1.9%)
		Objective value (maximum profit, revenue minus costs) [3]	1236.1 $[3]

Table 5 – Case 3 inputs and outputs

The approach chooses the most efficient way of bringing 450 MW of wind power to Nova Scotia. Since the cost of generation is identical for each node generating wind power, the most economical solution is to integrate 450 MW of wind power while laying the smallest possible number of cable kilometers in the sea. Since there is a variable cost on cables, the furthest generating node is generating less power than other nodes. N7 is too far away, the model does not build any cable to integrate it. We observe also that the network topology here is purely radial since there is no value attributed to having redundancy in the grid.

[3] This value does not represent the result of a cost-benefit analysis. Parameters are defined to test the model in different conditions.

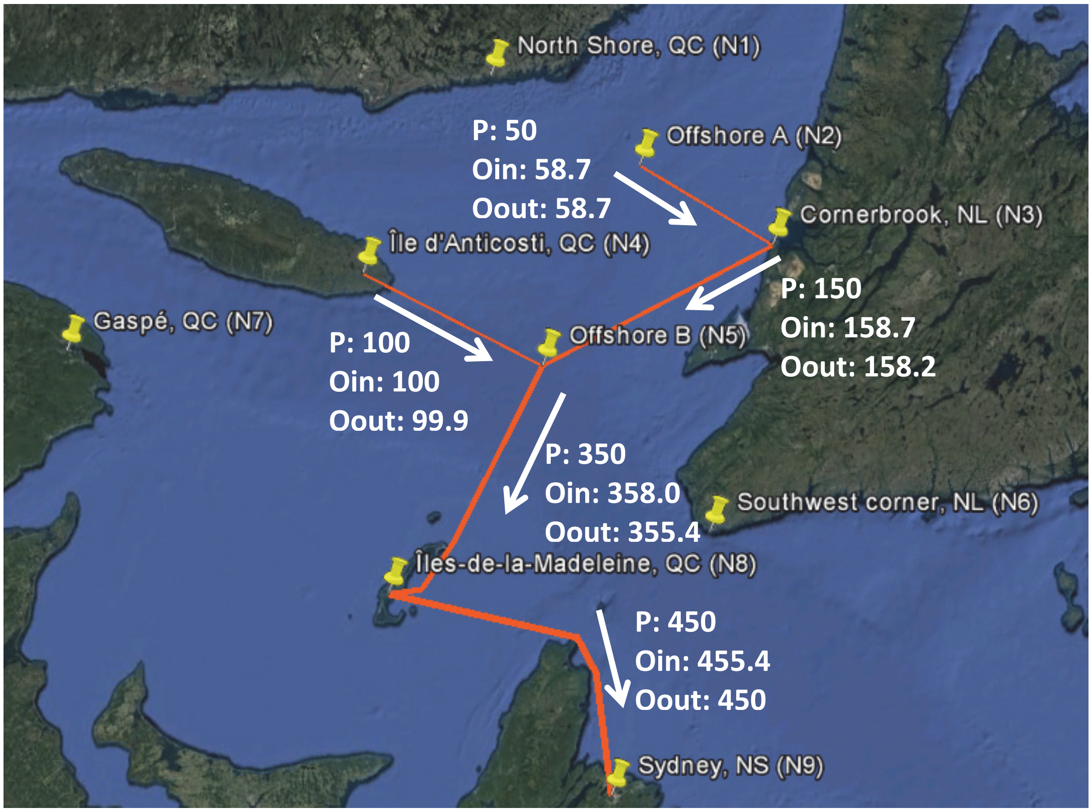

Figure 11 – Power flow in MW, Case 3 (P: Planning; O: Operations) – background map: Retrieved from Google Earth [42]

The main goal of this case was to build a wind power collector, but looking at Figure 11, we can see that the system connects two far-flung diesel-burning parts of Hydro-Québec's network (Anticosti Island and Magdalen Islands) to the mainland using a DC grid. Moreover, since the system links N8 by two cables and that there are different routes to two different mainland nodes (N3, N9), the Magdalen Islands could even benefit from route redundancy and close definitely the diesel power plant while maintaining a very good reliability status.

4.3.4 Case 4: Link between Côte-Nord, Magdalen Islands and Gaspé

Increasing the complexity of the problem, the fourth case will look at a system that collects wind power, transmit bulk hydropower and integrates a small far-flung grid. A new major load in Gaspésie could trigger important investments on HQ's network. To power such a new load, it would be worthwhile to consider a high capacity transfer across a link from the Côte Nord to Gaspésie. Furthermore, to increase complexity from previous cases, the system will need to provide 60 MW to the Magdalen Islands where we assume no generation is running.

Parameters (input)		**Variables (Output - Results)**	
Demand at N7 Demand at N8	850 MW @ 10$/MW 60 MW @ 10$/MW	**Planning:** Links Gen at N1	 N1-N4, N1-N5, N4-N7, N5-N7, N5-N8 910 MW
		Objective value (maximum profit, revenue minus costs)[4]	5957.3 $[4]
Gen at N1 Gen at N2, N3, N4, N5	1000 MW @ 2 $/MW 100 MW @ 5 $/MW for each node	**Operations:** Gen at N1 Gen at N4 Gen at N5 Gen at N2, N3	 859.0 MW 4.2 MW 63.8 MW 0 MW
Variable cost of link	0.001 $/MW*km	Voltage at N1	1.000 pu (set)
Fix cost of link	1 $/km	Voltage at N4	0.992 pu
Link maximum capacity	**500 MW**	Voltage at N5	0.993 pu
		Voltage at N7	0.980 pu
		Voltage at N8	0.991 pu
		Losses in cables	17.0 MW (1.8%)
		Objective value (maximum profit, revenue minus costs) [4]	5725.5 $[4]

Table 6 – Case 4 inputs and outputs

The introduction of a maximum capacity for each cable and of two different but parallel ways for power to flow shows the model's ability to reroute power by changing the source of generation (see Figure 12). The planning model chooses N1 to generate all the power required to meet demand, but without other generators, the power flow solution would be infeasible. Since the links are all connected, power flow rules apply on how the power dispatches between the links. For the present case, N5 has to generate power for the solution to meet the power flow constraints while capping the power flow to 500 MW in each link.

[4] This value does not represent the result of a cost-benefit analysis. Parameters are defined to test the model in different conditions.

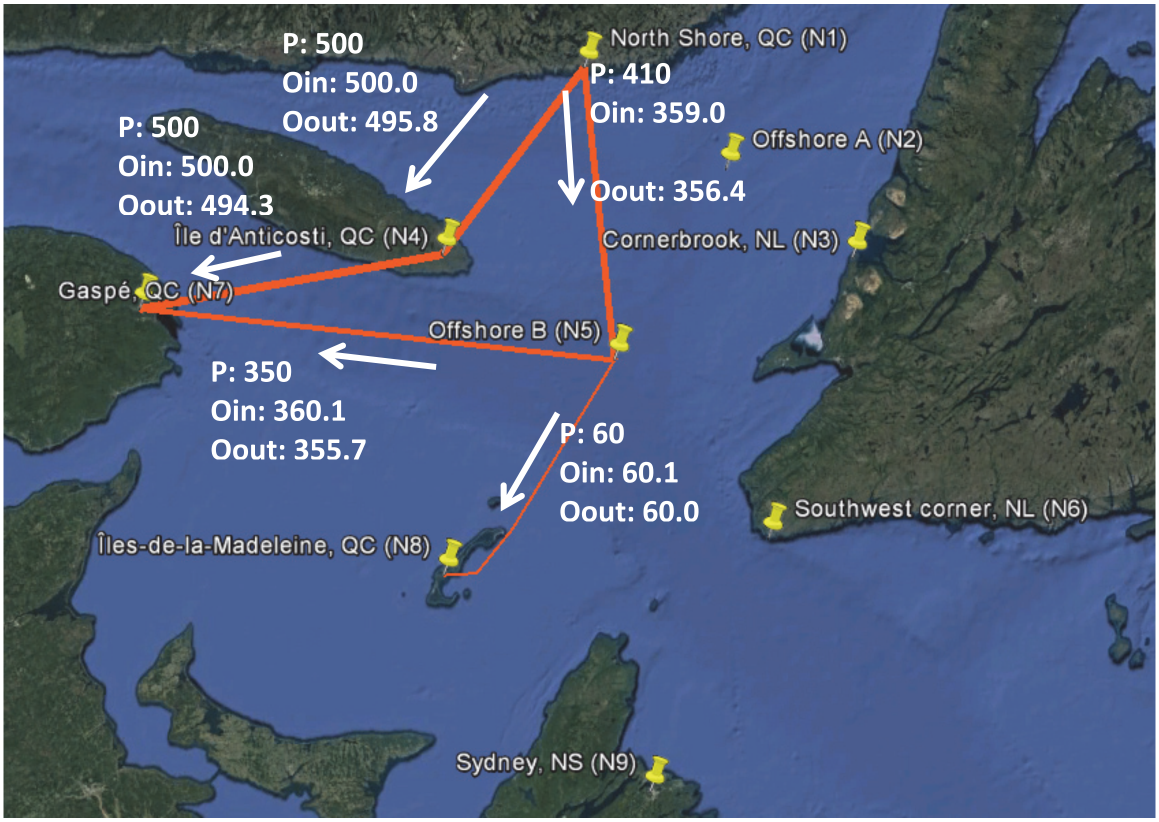

Figure 12 - Power flow in MW, Case 4 (P: Planning; O: Operations) – background map: Retrieved from Google Earth [42]

As seen from the power flows in Figure 12 and the generated power values in Table 6, N4 generates power that offsets the losses in cable N1-N4 (4.2 MW) so that N4-N7 can transmit its maximum power flow of 500 MW and N5 generates just enough power (63.8 MW) so that the power equations are valid and that N7 receives 850 MW.

It is worth noting that the same system without generation capability at the intermediate nodes in N4 and N5 would not be able to transmit as much power. Without generation in N4 and N5, the system would be able to transmit less power to N7 (817 MW instead of 850 MW) while generating 893.7 MW instead of 859.0 MW in N1 because of the maximum capacity of 500 MW per link. The transmission limit on this particular system would therefore vary in real-time with respect to available wind generation.

The other limitation of this system is that it provides only one link to power the Magdalen Islands, which means that it could not be the only source of electricity in the islands. To satisfy the N-1 reliability criterion, the diesel-powered plant would need to stay open.

4.3.5 Case 5: Interconnection Québec – Newfoundland – Nova Scotia

A DC grid system permits to maximize the power transmitted while minimizing the costs associated with the number of AC-DC converters in the system. The following case will increase complexity with respect to case 4 by joining the two interconnection links seen in cases 2 and 4. The need is to serve load both in Québec (N7) and in Nova Scotia (N9) while generating on the North Shore (N1) and in Newfoundland and Labrador (N6). Offshore windfarms will again play a role in the operations model and will help maximizing the transmission limit

Parameters (input)		**Variables (Output - Results)**	
Demand at N7 Demand at N8 Demand at N9	800 MW @ 10$/MW 60 MW @ 10$/MW 800 MW @ 10$/MW	**Planning:** Links Gen at N1 Gen at N6	 N1-N4, N1-N5, N4-N7, N5-N7, N5-N8, N5-N6, N6-N9, N8-N9 1000 MW 660 MW
		Objective value (maximum profit, revenue minus costs)[5]	10534.0 $[5]
Gen at N1 Gen at N6 Gen at N2, N3, N4, N5, N8	1000 MW @ 2 $/MW 1000 MW @ 3 $/MW 300 MW @ 5 $/MW for each node	**Operations:** Gen at N1 Gen at N4 Gen at N6 Gen at N8	 943.0 MW 4.2 MW 484.0 MW 253.8 MW
Variable cost of link	0.001 $/MW-km	Voltage at N1	1.000 pu (set)
Fix cost of link	1 $/km	Voltage at N4	0.992 pu
Link maximum capacity	**500 MW**	Voltage at N5 Voltage at N6	0.991 pu 0.991 pu
		Voltage at N7	0.980 pu
		Voltage at N8 Voltage at N9	0.989 pu 0.981 pu
		Losses in cables	24.9 MW (1.5%)
		Objective value (maximum profit, revenue minus costs) [5]	9655.4 $[5]

Table 7 – Case 5 inputs and outputs

[5] This value does not represent the result of a cost-benefit analysis. Parameters are defined to test the model in different conditions.

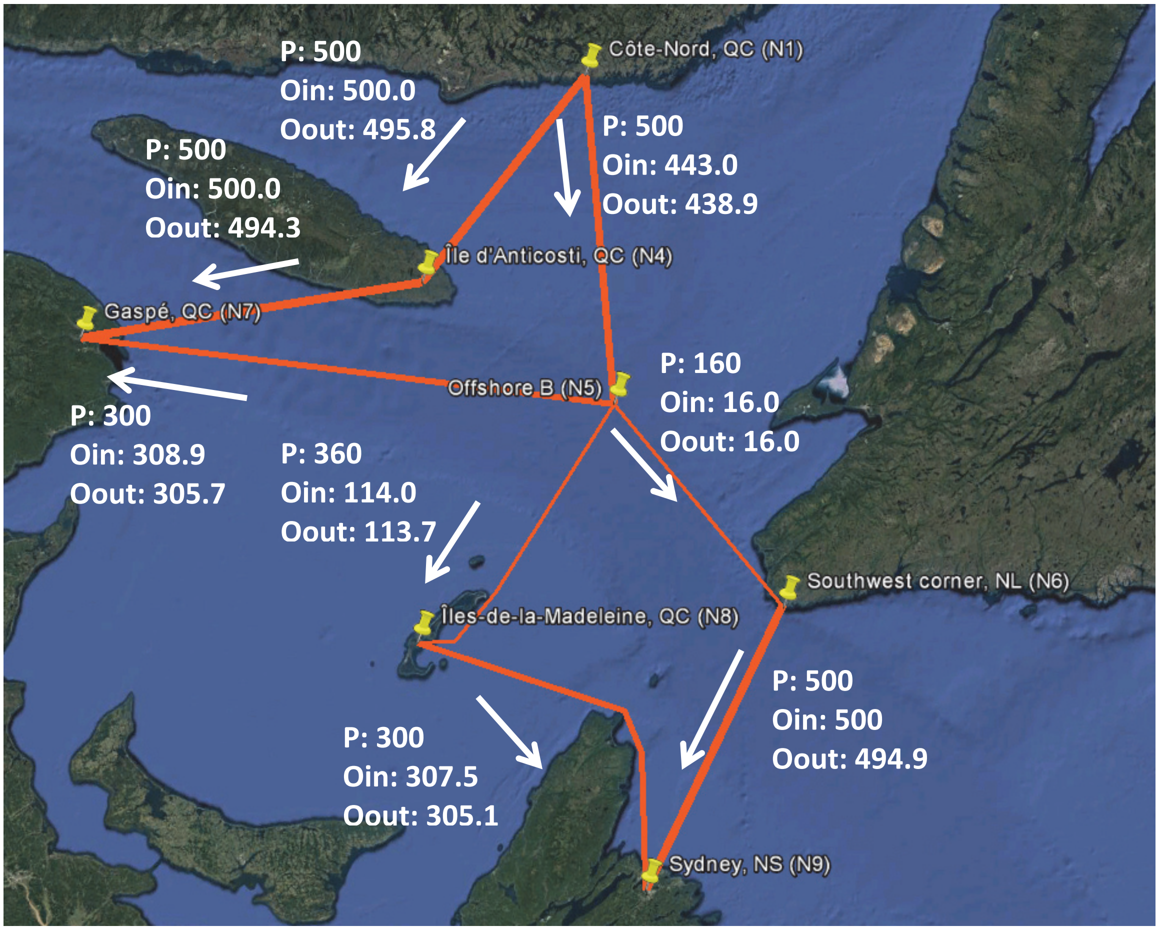

Figure 13 - Power flow in MW, Case 5 (P: Planning; O: Operations) – background map: Retrieved from Google Earth [42]

From Figure 13, we see that the operations case is very different from the planning case because of the huge effect of the power flow constraints. The planning case chooses its generation only in Côte-Nord (N1) and Newfoundland (N6), but this is not a feasible solution in the operations evaluation phase. The operations solution shows the huge potential of adding targeted offshore generation at the right location to maximize transmission limits and thus find a solution to meet demand while meeting the power flow constraints.

Connecting isolated grids is not the main goal here, but we can see from Figure 13 that the Magdalen Islands and Anticosti, both isolated fuel-burning grids, get a very reliable (N-1 secure) connections to the provinces' principal grids (two links each). The optimizer connects both systems to the provincial grids even if no constraint is set to connect them. They can also participate to power generation by building offshore windfarms. They can even sell electricity at a premium price with respect to the onshore generators because of their favorable positions in the grid.

Observing Figure 13, one could question the importance of building the N5-N6 link since its power flow in the operations solution is only 16 MW. To make sure this link is profitable, the network planner would look at other situations where power could be generated elsewhere. This link provides flexibility for system operators around the Gulf.

4.3.6 Summary of all cases and security criterion

Each case can fulfill three roles: Link the Magdalen Islands to the mainland, collect offshore wind power and/or transmit bulk power. Here is a list of all cases with what roles they fulfill:

	Link to the Magdalen Islands (N8)	Wind collector	Bulk power transmission
Case 1	Yes – 1 link to N8	No	No
Case 2	No	No	Yes – N6-N9
Case 3	Yes – 2 links to N8*	Yes – N2, N3, N4, N5*, N8*, N9	No
Case 4	Yes – 1 link to N8	Yes – N4*, N5*	Yes – N1*-N7*
Case 5	Yes – 2 links to N8*	Yes – N4*, N8*	Yes – N1*-N6*-N7*-N9*

Table 8 – Summary of all cases studied in Section 4

The nodes indicated in green are connected to two different paths that lead to:

- at least two onshore nodes for an offshore node
- at least one other onshore node for an onshore node.

Nodes with asterisks satisfy the N-1 criterion, meaning that they will stay connected to a onshore node if one of any link of the system is disconnected. Looking at Table 8, we can conclude that case 5 shows the most reliable network. Deploying large-scale DC grids including multiple closed-loops will yield networks that are more secure.

From this initial design, the next chapter will study the refined design of the DC grids and the economic advantages of links between large AC grids.

5 REFINED DESIGN OF DC GRIDS AND PROPOSED FURTHER STUDIES

This chapter shows a range of possible situations to analyze the opportunity of building a multi-terminal DC system in the Gulf of St. Lawrence. We will take a deeper look at cases 1 and 5 from Chapter 4 by optimizing the system through multiple conditions and using more system options. Finally, we will pose what could be done to further study DC multi-terminal systems optimization.

5.1 System voltage and cable resistance

Optimizing voltage level and cable size is a necessary step of planning a power system. In the case of the DC grid planning approach built in this thesis, it can be done by varying the resistance parameter. The voltage level should have a larger impact than the cable conductor size on the cost of the system since the cost of converters and the insulation thickness on the cable both depend on the voltage level. To optimize the system, we will therefore adjust the system voltage first and then the cable conductor size.

Case 1, in Chapter 4, showed very small power losses (Table 3). Decreasing system voltage can change the cable and the AC-DC converters cost and will increase power losses. We can expect the losses to vary exponentially with the voltage level from Ohm's law. Take a link from A to B, the typical equation for power losses is:

$$P_{losses} = R_{AB} I_{AB}^2 \tag{5-1}$$

The current from A to B can be found at node A by:

$$I_{AB} = \frac{P_A}{V_A} \tag{5-2}$$

Combining both equations, we obtain:

$$P_{losses} = R_{AB} \frac{{P_A}^2}{{V_A}^2} \tag{5-2}$$

For the same sent power, we therefore expect the power losses to decrease with the square of the rated voltage.

Case 1 in Chapter 4 assumed a voltage of 320 kV. As seen in Table 3, the power losses account for 0.2% of the power transmitted. Looking at other cases, 0.2% is low and the planner could probably save money by designing a lower voltage system. Let us assume that he aims to keep power losses under a reasonable value of 1%. Changing this voltage level, the model outputs the following results:

Voltage (kV)	Resistance (pu/km)	Losses (MW)	Losses (%)
100	0.0001200	1.079	1.77%
150	**0.0000533**	**0.47**	**0.78%**
200	0.0000300	0.263	0.44%
250	0.0000192	0.168	0.28%
300	0.0000133	0.116	0.19%
320	0.0000117	0.102	0.17%

Table 9 – Power losses vs Voltage level, case 1

Plotting losses vs voltage level in Figure 14, we can see that losses decrease with respect to the voltage level, as expected.

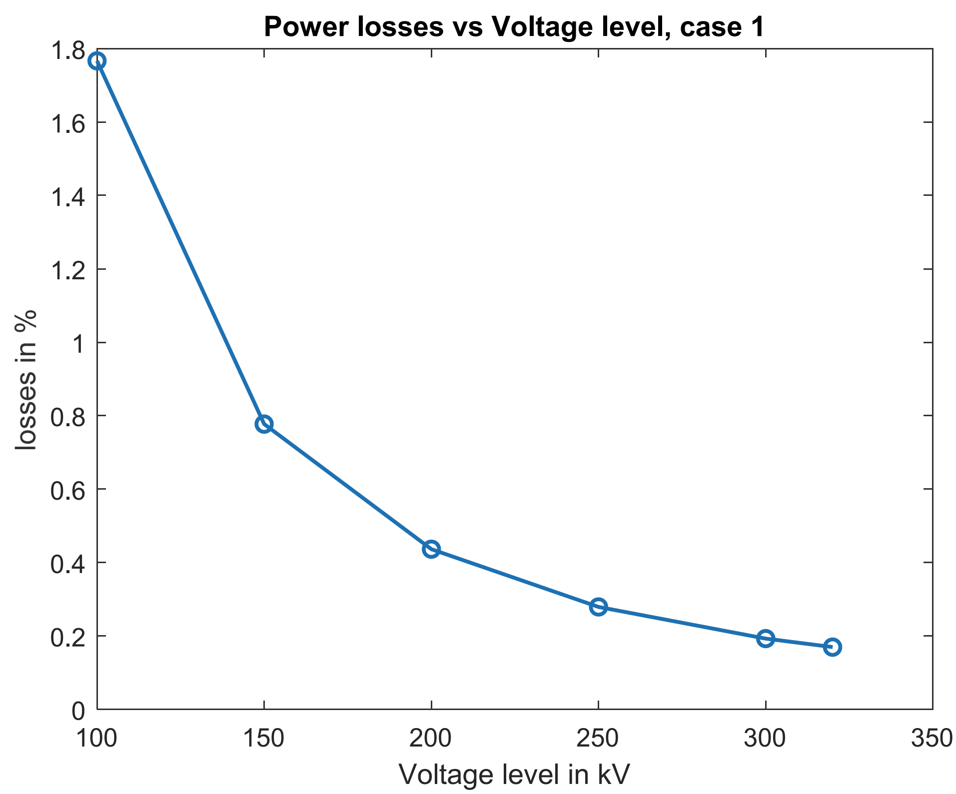

Figure 14 – Power losses vs Voltage level, case 1

To keep power losses under 1%, the planner would select 150 kV as the system's voltage level.

Until now, we assumed the cable conductor area to be 1500 mm^2. To further refine the optimization of the system proposed in case 1, we can try varying it. An ABB document [43] shows that resistance decreases quadratically with the area of the cable used. Varying the resistance according to ABB's values, we obtain:

Area (mm^2)	**Resistance (Ω/km)**	**Resistance (pu/km)**	**Losses (MW)**	**Losses (%)**
~~95~~	~~0.193~~	~~0.0008578~~	-	-
120	0.153	0.0006800	7.457	11.05%
150	0.124	0.0005511	5.74	8.73%
185	0.0991	0.0004404	4.403	6.84%
240	0.0754	0.0003351	3.229	5.11%
300	0.0601	0.0002671	2.516	4.02%
400	0.047	0.0002089	1.931	3.12%
500	0.0366	0.0001627	1.482	2.41%
630	0.0283	0.0001258	1.133	1.85%
800	0.0221	0.0000982	0.877	1.44%
1000	0.0176	0.0000782	0.694	1.14%
1200	**0.0151**	**0.0000671**	**0.594**	**0.98%**
1400	0.0126	0.0000560	0.494	0.82%
1500	0.012	0.0000533	0.47	0.78%
1600	0.0113	0.0000502	0.442	0.73%
1800	0.0098	0.0000436	0.383	0.63%
2000	0.009	0.0000400	0.351	0.58%
2200	0.008	0.0000356	0.312	0.52%
2400	0.0073	0.0000324	0.284	0.47%

Table 10 – Power losses vs conductor area, case 1

The first conductor size in Table 10 (95 mm^2) has a thermal capacity smaller than the required transmitted power, so we cannot consider it in this design. Plotting losses vs conductor area, we can see that losses decrease with respect to the conductor area. The losses curve has a nearly asymptotic behaviour after decreasing to less than 1%.

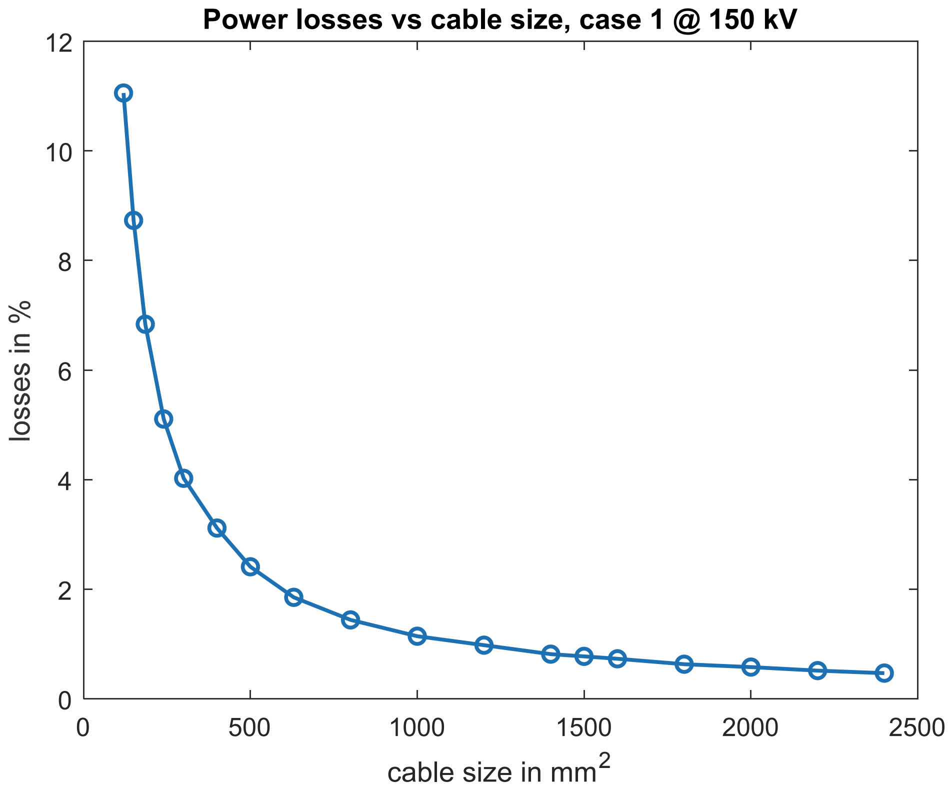

Figure 15 – Power losses vs cable size, case 1

A planner that wants to keep power losses under 1% of the power delivered would therefore choose to build a 150 kV DC system using a cable with a conductor area of 1200 mm². Section 6.1 proposes further work that one could do collaborating with cable and converter manufacturers to optimize automatically conductor area and voltage level.

5.2 Comparing the traditional planning approach with a multi-terminal system approach to power the Magdalen Islands

The economic performance of projects connecting smaller and isolated grids to the main network is often jeopardized by the very high cost of HVDC equipment, especially when redundancy is required to ensure a good reliability level. The very weak load factor of isolated networks can also be an issue; HVDC equipment is more economical when used at a higher load factor.

5.2.1 Case 1 profitability – Gaspésie - Magdalen Islands

For example, assume that the system optimized in section 5.1 is not profitable on a year round basis:

Peak demand at N8 [44]	45.28 MW
Average demand at N8 [44]	22.25 MW
Average energy cost at N7	60 $/MWh
Average energy cost at N8	100 $/MWh
Energy sold at N8 over a year	195 GWh
Energy bought at N7 over a year (losses = 1%)	197 GWh
Generation cost (year)	11.8 $
Revenue (year)	19.5 $
Operational profit (year)	7.7 $
NPV of expected profit over 50 years	**206 $**
(Assuming 2% inflation rate and 5% discount rate)	
Total cost of project (assuming costs listed in case 1)	**255 $**

Table 11 – Economic analysis of case 1[6]

From data in Table 11, we can see that the project is not profitable since the NPV of the expected profit for the next 50 years (lifespan of the submarine cable) is lower than the project cost. This is caused by the load factor of the cable that is very low; say that the capacity of the cable is mirrored on the peak demand at N8 (45.28 MW), the load factor of the cable would be **49%**. A careful network planner would also set a higher capacity for the cable (probably at least 60 MW), since he will plan to meet the power needs of the islands for the next 50 years. This project is hard to make profitable since the equipment installed is not used at its full potential.

5.2.2 Case 1' profitability – Gaspésie - Magdalen Islands - Nova Scotia

Introducing a modification of case 1, case 1', where Hydro-Québec could sell power in Nova Scotia through the Magdalen Island interconnection. Adding a cable from N8 to N9, we could increase the load factor of the system. By experience, the load factor of links between Québec and other networks is around 80%. Let us set a realistic price of electricity in Nova Scotia (N9) to 80 $/MWh and keep the average cost of power in Québec (N7) at 60

[6] This is not a real life scenario. Parameters are defined to test the model in different conditions.

$/MWh. The resulting system consists of two cables: N7-N8 and N8-N9. This multi-terminal system has multiple advantages compared to a single cable from N7 to N8:

- It gives a better service to the islands (N-1 criterion is met since the islands can be powered from Québec or Nova Scotia if only one cable is unavailable)
- It yields significantly more revenue from the higher load factor
- It could power the islands in the event their load grows faster than planned (system has a higher capacity and could even deliver power from Québec and from Nova Scotia to the islands)
- It diversifies the energy source of the islands. Prices of electricity may vary according to market rules, so power could be cheaper in Nova Scotia, meaning potentially cheaper electricity for the islands
- It could import power in Québec from Nova Scotia, for network reliability or commercial purposes.

The next figure shows the case 1' on the Gulf of St. Lawrence map:

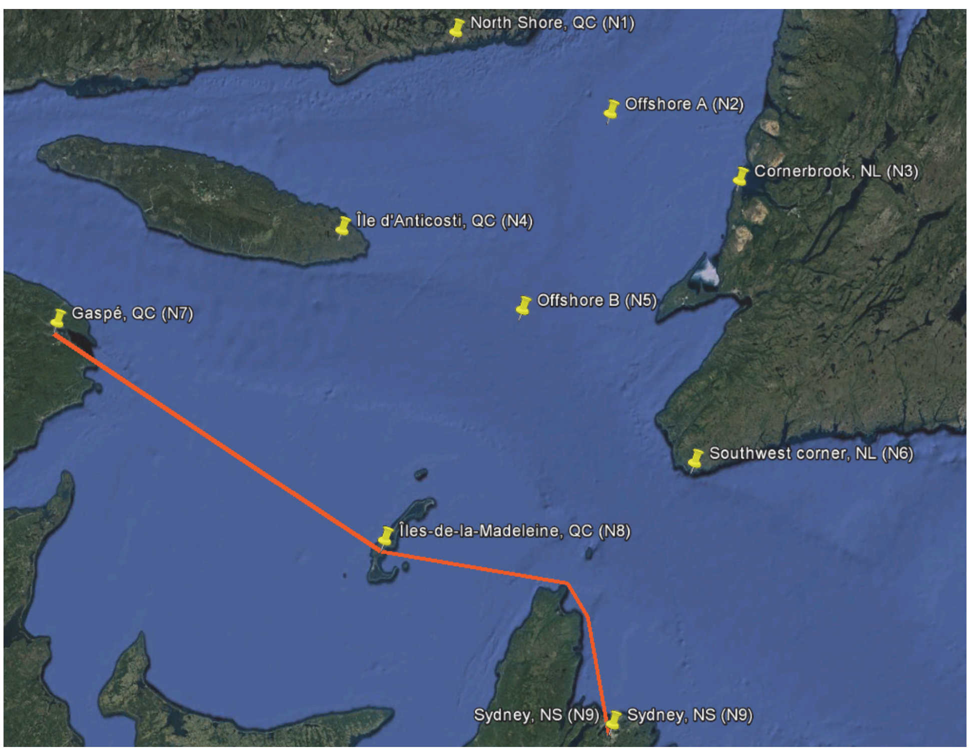

Figure 16 – Case 1' network map – background map: Retrieved from Google Earth [42]

The next table shows the economic analysis of such a multi-terminal system:

Peak demand at N8 [44]	45.28 MW
Average demand at N8 [44]	22.25 MW
Peak demand at N9	100 MW
Average demand at N9	80 MW (80% of peak)
Average energy cost at N7	0.060 $/GWh
Average energy cost at N8	0.1 $/GWh
Average energy cost at N9	0.08 $/GWh
Energy sold at N8 over a year	195 GWh
Energy sold at N9 over a year	701 GWh
Energy bought at N7 over a year (losses = 1.3%)	908 GWh
Generation cost (year)	54.5 $
Revenue (year)	75.6 $
Operational profit (year)	21.1 $
NPV of expected profit over 50 years	**565 $**
(Assuming 2% inflation rate and 5% discount rate)	
Total cost of project (assuming costs listed in case 1)	**501 $**

Table 12 – Economic analysis of case 1'[7]

Table 12 shows that the load factor of the interconnection between Québec and Nova Scotia takes the energy exports from Québec to another level. Sending more energy from N7 means more profits from the installed equipment. The total load factor of the system is **70%**.

Going further, we will now study the profitability of case 5 using the same method to improve the load factor of the system.

5.2.3 Case 5 profitability – Case 1' vs Case 5

With case 1', the business case of the project of connecting the Magdalen Islands to the mainland is taking form. Going another step further, we can analyze the profitability of case 5 with the same method. For the sake of this analysis, we add one more constraint in the model. Generation at N1 and N6 must be equal since the model cannot optimize generation with respect to time since we are working here with an average case. Section 6.1 describes

[7] This is not a real life scenario. Parameters are defined to test the model in different conditions.

what could be done as further work to optimize generation with respect to time. Table 14 shows the economic analysis of such a multi-terminal system:

Node	Peak demand	Average demand/losses	Average generation	Energy price	Energy bought/sold
N1	-	-	659.25 MW	0.05 $/GWh	5,779 GWh
N6	-	-	659.25 MW	0.05 $/GWh	5,779 GWh
N7	800 MW	640 MW	-	0.06 $/GWh	5,610 GWh
N8	45.28 MW	22.25 MW	-	0.10 $/GWh	195 GWh
N9	800 MW	640 MW	-	0.08 $/GWh	5,610 GWh
losses	-	16.26 MW	-	-	143 GWh

Table 13 – Economic analysis of case 5 - 1[8]

Generation cost (year)	577.9 $
Revenue (year)	804.9 $
Operational profit (year)	227.0 $
NPV of expected profit over 50 years (Assuming 2% inflation rate and 5% discount rate)	**6,081 $**
Total cost of project (assuming costs listed in case 1)	**1,930 $**

Table 14 – Economic analysis of case 5 - 2[8]

The load factor of the case 5 system is **79%**. The total load factor is approaching the interconnection load factor standard of 80% since the load of the islands is very small compared to the total capacity of the system.

The model limits the analysis of these cases since that a full hour-by-hour analysis would be required to build precise business cases. Average cases still show the huge impact of the load factor on the profitability of projects.

[8] This is not a real life scenario. Parameters are defined to test the model in different conditions.

6 CONCLUSION

This thesis has developed a heuristic technique to design large-scale DC grids that can link isolated AC grids to large AC grids, integrate offshore wind resources and transmit bulk power between large AC grids. To find a solution efficiently so that network planners can use the model on an everyday basis, we split the problem in two parts: the design of the DC grid, optimized by MILP and the actual power flow computation of the DC grid, optimized by NLP.

While analyzing cases built by the model in Chapter 4, we noted that the linear part of the model (MILP, Planning approach) can choose DC links to optimize the design of large-scale DC grids and that the non-linear part (NLP, Operations approach) can compute the DC power flow accurately and yields precise power flow and power losses values. At the end of Chapter 4, we also noted that large-scale DC grids are more reliable than a single DC link. Chapter 5 refines the design of the DC components of the system and includes examples of economic analyses to show that DC grids that interconnect two large AC networks should exhibit a larger load factor, which should result in higher profit than links linking isolated small AC grids to a larger AC grid. Finally, we suggest further research to improve the model in the next section.

6.1 Proposed further research

Further research could be done to make the model more useful in real life applications. First, the planner can choose the system characteristics to optimize cost. Second, an analysis hour-by-hour can help build precise business cases to study projects. Third, greenhouse gas emissions price could be inserted in the model to reflect policy on greenhouse gas emissions reductions.

6.1.1 System voltage and cable size optimizer module

Section 5.1 showed that the planner chooses the system voltage and cable size to optimize costs including power loss levels. A researcher associated with manufacturers could design an automatic HVDC optimizer module. Knowing already the price of electricity, the model could easily output the cost of losses.

Having the costs for multiple voltage and cable size scenarios would allow comparing the differential costs of infrastructure with the differential costs of power losses for each scenario. The model would have to choose from a selection of resistances per kilometer that would be associated with a converter cost and a cable cost. This resistance and cost table could be built in association with cable and converters manufacturers. The planner could then use this full optimizer to design the right DC system for each situation.

6.1.2 Hour-by-hour market simulation

Further work on the model should be also focused on making it possible to study power flow hour by hour and simulate energy market action over at least a full year. The model would then be able to build precise business cases for multi-terminal submarine HVDC projects.

6.1.3 Greenhouse gas emissions price

Climate change is leading power generating companies to adopt cleaner power generation, transitioning from fossil fuel power plants to clean wind, solar or hydro generation. Governments can enact policy to put a price on each emitted carbon ton, which in turn could be included in the model. Planners could then use the model to measure the effect of new interconnexions and new offshore wind generation on greenhouse gas emissions reduction.

6.1.4 Optimization research (convex relaxations of optimal power flow)

The development of a solver adapted to optimal power flow problems could make it possible to solve the network design problem and the power flow problem in a single model with reasonable computational time. Recent advances promise that under sufficient conditions, using convex relaxation of the power flow equations, one can recover a globally optimal solution [45], [46]. Such advances can lead to better solutions and to a problem formulation where the network planning and operations could be co-optimized explicitly.

6.1.5 Security constraints

One could develop a constraint implementing the N-1 criterion for given nodes to force a certain level of network reliability or at least put a price on it. This would be very useful to force the model to give a reliable service to isolated populations.

Network planners will use DC grids in the future to integrate renewable energy sources in AC grids; they will need efficient tools to optimize the DC grid designing and planning process. This thesis provided such a tool and proposed further research to make it even more useful to network planners.

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