A Regional Electricity Hub for Energy Transitions

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

I would like to acknowledge the names of my co-authors who contributed to the research described in this dissertation, and these include: Prof. Jatin Nathwani and Adjunct Assist. Prof. Emre Çelebi

Abstract

The transition to a low-carbon energy economy will remain a cornerstone of national energy policies of countries committed to the climate change accord for decades to come.

We highlight the need for transmission investment as one key policy instrument among others to achieve an energy economy with lower dependence on fossil fuels. We propose an enhanced role for investing in transmission capacity in support of large-scale inter-regional electricity trade to allow effective fuel switching among countries through a physically connected transmission system and functioning markets. A conceptual framework of Regional Energy Hubs Regional Electricity Hub (REH) is proposed. The cost minimization model for the transmission investment strategy integrates the:

1. key geopolitical parameter for countries that are geographically close in a region but under different political jurisdictions, judged as stable and receptive to firm trading arrangements,

2. economic parameter related to the fuel mix where the differences in a country's supply and demand characteristics are significant enough for allow mutual benefits to be realized through cost reduction,

3. environmental parameter linked to a country's carbon intensity that could benefit from the resources of a neighboring jurisdiction with lower intensities, and

4. financial parameter for each country within a region capable of attracting investment capital for a common interest project.

The proposed REH is an innovative framework that is the basis for a cost-effective but environmentally beneficial strategy for integrating the energy supply mix of several

countries. The countries are geographically contiguous but operate as different jurisdictions with diverse geopolitical, economic, environmental, and financial constraints. For a regional energy hub, the transmission capacity investments act as one of the key policy instruments allowing recognition of the REH interconnectors as the links. We have applied the REH Framework for two case studies: one in developing markets in South Eastern Europe and a developed market in the North American context.

In the first case study, we have utilized the REH Framework's geopolitical parameter to select a set of countries with developing markets to form a regional electricity hub and applied an economic dispatch model to minimize generation costs and reduce CO2 emissions simultaneously in the newly formed REH's total energy fuel mix. The preliminary results for this case study indicated that the total cost minimization approach for the region results in a net benefit in favor of the transmission investment. The REH enables transmission capacity to achieve reduced cost generation and emissions by physically interconnecting markets in a predefined region, essentially enabling fuel switching of carbon based power generation.

In the second case study, we have utilized the REH Framework's financial parameter for a developed market, e.g., the PJM's capacity market, to identify the potential value of interconnectors by employing a financial option theory to value capacity options between a generation and an interconnector. Results of our analysis for the existing and planned projects provides strong evidence of the value of transmission capacity as an option within the REH Framework and points to a pathway to achieve decarbonisation at lower costs across a region instead of focusing only on investments in generation capacity.

Following ratification of the Paris 2015 Climate Change Accord, all national governments are committed to a reduction of Greenhouse Gas Emissions (GHG) within their jurisdictions. This puts a premium on identification of practical and cost-effective pathways for achieving the national targets for reducing GHG within a regional context. The case studies demonstrate the critical role of a REH in delivering tangible benefits through interconnectors that would otherwise not be achievable if each countrys energy system was isolated from its contiguous neighbours.

The REH allows integration of a diverse mix of generation supply of different countries to yield maximum financial value and GHG reduction potential through transmission interconnectors. To enable the transition to a low carbon energy system of the future, REHs offer an expedient pathway through development of transmission interconnection capacity consistent with geopolitical, environmental and financial criteria developed here.

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Last but not least, Arman -my dear son- one piece of advise to you. The world is tough out there. If you want to be happy, make your own decisions and follow-through.

Dedication

To my dearest family: Güliz - Arman

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List of Abbreviations

BG Bulgaria 39

CAISO California Independent System Operator 65

CfD Contract for Differences 2

DC Direct Current 46

ENTSO-E European Network of Transmission System Operators for Electricity 41, 102

ENTSO-G European Network of Transmission System Operators for Gas 41

ERCOT Electric Reliability Council of Texas 6, 8, 64

EU European Union 7, 8

FERC Federal Energy Regulatory Commission 62, 66, 75

FIT Feed-in-tariff 2

FTR Financial Transmission Rights 10, 11

GHG Greenhouse Gas Emissions vi, vii, 1, 3, 15, 25, 26

GR Greece 39

GW Giga Watt 1

HVDC High Voltage Direct Current xv, 71, 73, 75, 81

IESO Independent Electricity System Operator 72

ISO Independent System Operator xvi, 6, 62, 63, 75

LNG LiquidNaturalGas 3, 15

LP Linear Programming 46, 50

MISO Midcontinent Independent System Operator 7, 73

NYISO New York Independent System Operator 72

PJM Pennsylvania New Jersey Maryland Interconnection xii, xv, 6, 7, 16, 61–69, 71–73, 75, 80, 81, 103

PTR Physical Transmission Rights 10

PX Power Exchange 6

QTU Qualifying Transmission Upgrade 65

REH Regional Electricity Hub v, vii, xii, xiv, xvi, 11, 13, 14, 16–18, 20, 22, 23, 25–31, 35, 36, 39–43, 46–48, 50–52, 61–64, 66, 67, 71, 75, 80–82, 84, 85

RO Romania 38, 39, 50, 51, 80

RPM Reliability Pricing Model 65, 69

RTEP Regional Transmission Expansion Planing 65, 66, 75, 81

RTO Regional Transmission Operator xvi, 62, 63, 75

SPP Southwest Power Pool 72

TIC Total Investment Cost 72

TR Turkey 38, 39, 50, 51, 80

TSO Transmission System Operator 6, 12, 30

UNFCCC United Nation's Framework Convention on Climate Change 31, 41

WTO World Trade Organization 31, 39, 102

Chapter 1

Introduction

The threat to the global climate arising from the use of fossil fuels and emissions of GHG, is a primary driving force for the transition of the energy system away from fossil fuels to non-carbon sources of electricity generation.

The pathways to a low-carbon energy economy are influenced by (a) supply and demand, (b) technological developments, (c) evolution of markets and regulatory structures and (d) geopolitical considerations at the national and regional levels.

For the supply and demand balance of electricity, historically, generation capacity has met the demand (load) for a particular state, province or a country. Centrally planned large-scale generation (coal, hydro and nuclear units in Giga Watt (GW) installed capacities) were constructed, operated and owned by integrated utilities either privately owned or by the state. The organizing principle of the electricity sector has been on meeting demand with supply through a transmission and distribution system allowing control and management of all flows within the jurisdiction.

However, the energy sector is now changing with increased emphasis on renewable energy resources such as wind, solar, biomass, geothermal and distributed energy resources within the overall energy supply mix. These resources are not only spread geographically but also exhibit variability in output that has an intermittent characteristic where the generation source may not be available as a dispatchable resource to meet system needs continuously. The emerging diversity of the generation resources introduces a level of complexity different from historical experience.

Transmission lines in most of the developed countries are recognized as aging infrastructure, and the capability of this legacy system to meet the challenges of new intermittent generation resources represents an opportunity for new interconnectors and regional integration of supply resources through electricity trade. Therefore, there is not only a need for new construction of lines but also a need to rethink the way we look at transmission lines to help us tap more into the availability of these intermittent renewable energy sources (Hogan et al., 2011). There is also a greater role for transmission and distribution for a "smarter" grid integration as electric powered vehicles become important sources of new demand (ENTSO-E, 2017). The role of the electricity system is changing from a simple focus on large-scale generation, and delivery to managing end-use energy services and to accommodate distributed energy resources to improve overall system efficiency.

In this context, the role of electricity markets is also changing from getting the most economical pricing of resources to the development of optimal investment strategies. Therefore, the rationale behind the establishment of markets such as NordPool is shifting towards absorbing excess energy generated somewhere to be consumed elsewhere. Electricity day ahead markets operate well only for the baseload. With the integration of renewables into the supply mix, their intermittent nature is also reflected in their pricing from Feed-in-tariff (FIT) to Contract for Differences (CfD) contracting (Hern et al., 2013). It is expected with the upcoming low-carbon energy economy energy markets should also handle these issues

(ENTSO-E, 2017).

The geopolitical considerations of extraction and utilization of energy resources around the world are also becoming important not only for producers of that commodity (natural gas) but also for consumers and more importantly for the transporters of that resource as seen in the recent Russian and Ukraine crisis (Gabriel et al., 2012). Crisis whether geopolitical driven or through nature as in Fukushima nuclear accident, which had its effect on LiquidNaturalGas (LNG) prices around the world, affect the markets.

From the climate change perspective, the emphasis on energy policies towards a carbon-free future has been evident since the 1990s with the introduction of Kyoto protocol in 1997. With governments adopting various forms of feed-in-tariffs, renewable portfolio standards and policy support mechanisms for incenting the integration of the renewable sources into their fuel mix, it is clear that climate change challenge will continue to shape the energy sector developments from different perspectives (Mideksa and Kallbekken, 2010).

Global energy trends are putting a new set of pressures for the existing energy system as we are progressing towards a low-carbon energy economy. The new pressure requirements can be described as: robust and flexible as opposed to robust and rigid, which was the historical requirement. One way of answering to the flexibility requirement could be the transmission investment.

Transmission investment strategy can now be viewed through a different lens as new energy market requirements emerge to address the twin challenge of GHG reductions and adequate supply of cost-effective energy services. Therefore, regional electricity concept comes into play from a transmission investment angle. We believe the role of transmission interconnectors across a large region, connecting diverse markets, for effective utilization of remotely located renewable energy sources for carbon mitigation needs to be evaluated. Transmission investment decisions and the for assessment of value requires a fresh perspective.

The future energy markets will require robustness and flexibility to handle these aforementioned pressures at the infrastructure level before it moves into the markets. So, one option is to invest in the transmission capacity. This will not only help transition to low carbon energy economy but also will help better optimize and utilize generated electricity at the global scale with the help of transmission lines (Guy Chazan, 2017).

In summary, tomorrow‘s energy markets are facing many pressures from many perspectives whether supply and demand, technology, markets, geopolitical and the climate change. It seems that these pressures will not ease and the reliance upon fossil fuels will not decrease without a better understanding of the value that a regional electricity hub can deliver. The long term goal to reduce carbon generation in the decades ahead will require rapid integration of non-carbon sources of into the current global supply mix.

1.1 Literature Review

As mentioned in Sioshansi (2013), "electricity market reform was intended to increase the role of market forces throughout electricity sector and correspondingly to reduce the role of political forces." Reform drivers were based on competition, privatization, restructuring and regulation as depicted in Sioshansi (2013) so that governments can leave the control of the sector (monopoly) and transfer ownership to market players. The rationale was that proper implementation of the reform by the drivers as mentioned above could result in efficient investments, lowered costs and consequently better consumer experience whether in reliability or in pricing of electricity as a commodity. Therefore, as the market economy has evolved around the world, many countries have opted for, one form or another in reforming of their electricity market starting as early as the 1980s in Chile and the UK (Pollitt, 2012b), and have had functioning liberal electricity markets since 1990s (Stridbaek, 2006). Reforms have produced many positive results in many countries in moving their electricity sector from purely controlled by a government to market dynamics where prices have become the better reflection of costs.

This section reviews the rationale and background on electricity market reforms around the world and its impact on transmission investment processes before and after that reforms. Reform means separation of the electricity value chain activities so that each activity is a different business entity and paving the way for the establishment of the wholesale/retail power markets so that competition is encouraged. The literature review summarizes the evolution of energy markets with a focus on the importance of transmission investment rationale and concludes on by explaining existing knowledge gap as well as linking this gap with a clear definition of the research problem.

1.1.1 Electricity markets

There are four main parts in the electricity sector value chain: generation, transmission, distribution and market activities. In the generation, historically, electricity is generated by many different technologies depending on the heat source: coal, oil, gas or nuclear where the heat energy is used to heat the water to get steam, which turns the steam turbines coupled to a generator where electricity is produced. Transmission serves the purpose of transmitting electric power to distant locations. Once electric power reaches a certain location or a region, then it is distributed to a final consumer via the distribution network. Before the deregulation of the electricity industry, however state(s) around the world has seen vertically integrated utilities in which power generation, transmission, and distribution assets are organized under a single publicly owned entity (Joskow et al., 2008). Central planning agencies have overseen planning, investment, and execution stages before the restructuring. After the deregulation, states have separated these value chain activities into generation, transmission, and distribution (Cámara, 2013). The generation and distribution assets have been privatized whereas transmission has remained a natural monopoly where pricing was regulated, and open access to transmission services are provided.

Historically after the reform, electricity market enactment had somewhat different rationale than today‘s electricity markets for developing and developed countries. For example, Australian and New Zealand experience has been for better management of the hydro resources so that irrigation can be optimized for agriculture. The NordPool market, on the other hand, is due to its participating countries economic cooperation strategy and electricity sector was an extension of this cooperation. Whereas PJM had started out as part of the North American Electric Power System, which consists of Western Interconnection, Eastern Interconnection, and Electric Reliability Council of Texas (ERCOT) had economic and reliability rationale (Bhattacharya et al., 2012).

Electricity markets have the following value chain players: generators (state-owned or private) are to generate electricity, Transmission System Operator (TSO) to operate, control, balance the system physically to ensure security, distribution (private) to operate the system and distribute to the electricity to end user, power traders (in wholesale markets) to facilitate/enable trading among the market participants to balance their portfolio of customers, retailers to sell electricity to end users, ISO and Power Exchange (PX) are to efficiently administer the financial settlements of delivered energy. The arrangement of physical energy flows (trading) to end consumer, financial and administrative transactions (charging) define the fundamentals of market designs of that particular market, which may change from market to a market (Chawla and Pollitt, 2013). Therefore, market designs in North America and European Union (EU) are different in handling the roles of those mentioned above.

In EU and Nordic Countries operation of day ahead markets where double-sided auction (offers from generators and bids from large-scale buyers) takes place to identify the market clearing price of physical trading of baseload (minimum level of demand over a time), peak (maximum level of demand over a time) or off-peak (opposite of peak - where low demand over a time) products. Intra day market allows for the adjustments before the real-time market and finally spot or real-time market takes place for physical balancing of the electric system. Also, financial trading occurs for baseload or peak products. For transmission, operation of EU and Nordics countries are as follows: (i) transmission capacity allocation method for bilateral trades (physical or financial transmission rights or options), (ii) transmission capacity calculation method for day ahead market via flow- based market coupling for the EU or market splitting for NordPool, (iii) transmission capacity allocation method for the day ahead market via Implicit auction of inter-zonal capacity and congestion rent for intra-zonal transmission. Market clearing price is set at the zonal level.

In North America, PJM and Midcontinent Independent System Operator (MISO) markets are typically composed of four markets: energy markets, ancillary services, bilateral transactions, financial transmission instruments and capacity markets. Energy markets have two parts: (i) spot (real-time) market, and (ii) forward day-ahead market. The ancillary services market, similar to intraday market in EU , have: (i) regulation of real time market, and (ii) reserve day ahead market and bilateral trades (Over the Counter OTC- in EU) occur in two forms as physical and financial. Financial transmission markets have two typical markets: (i) financial transmission right, and (ii) auction revenue rights. Market clearing price is set at the nodal level. This review has not considered the supply offers/demand bids processing of the electricity markets. However detailed information from the EU and North America comparison can be found in Imran and Kockar (2014).

The lessons learned with the electricity sector deregulation also clarify the issues and challenges around the electricity markets and transmission investment. Although many standard prescriptions exist for the full deregulation and liberalization of the sector as mentioned in Hunt (2002) and Joskow et al. (2008), they have indicated that a well-functioning transmission investment framework is needed for efficient markets. As mentioned earlier, as wholesale markets are developed, it has introduced some significant problems such as congestion. Hence this hinders the efficient operation of wholesale markets even further. Many of the countries, regions, and markets did not see transmission capacity in moving parallel with the demand and new capacity. The regional investment in transmission capacity also had problems in many of the countries. Joskow and Tirole (2005) indicated that the regional transmission expansion capacity was realized in ERCOT but this was not sufficient enough because it was not part of the North American system. Therefore, markets were not coordinating the efforts needed to communicate between the markets, and one reason was a lack of market design similarities (Kassakian et al., 2011).

With the aforementioned global energy trends of the previous section, the transmission has a more significant role in energy markets around the world in integrating upcoming renewable sources, connecting markets with mutually beneficial energy fuel mixes, increasing wholesale trading, and reducing market power (Kassakian et al., 2011).

The current energy markets and their design will be insufficient in answering future requirements due to aforementioned reasons. Since the fundamental rationale behind it (irrigation, optimized use of hydros, economic efficiency) was different than today‘s and future requirements of energy. Therefore, the future energy markets will require a different rationale for their foundation: optimization of the world energy resources cooperatively: moving from a single view of parameters considering only the economic side to a wide array of parameters considering: political, economic, financial and environmental issues. Transmission investment may be one of the enablers of these requirements.

Today's electricity markets around the world must address a number of key issues with respect to the climate change, infrastructure as well as market designs as follows:

- The Climate change and its consequence of seeking reductions for in emissions (CO_2, NO_x) around the world have been recognized by the governments for years. Moreover, the industry has also recognized it and started to take action towards it. Hence, concepts such as the low-carbon economy or low-carbon energy market, low-carbon growth have been adopted by the industry and the governments work together to better manage the transition into this new era by switching to renewable energy resources or implementing energy efficiency measures (IPCC, 2017).

- Deciding on investment and/or replacement in value chain infrastructure: in generation (i.e., coal power and/or nuclear power plants); integrating renewable sources (Schumacher et al., 2009) and storage into their system (Pollitt, 2016); increasing energy trading among countries by connecting markets (Newbery et al., 2016); deciding on investment and replacement in transmission system (Hogan, 1999) while increasing reliability upgrades, generation interconnection, reducing congestion;

- overcoming market design issues preventing coordination among countries (Imran and Kockar, 2014); while reducing market design differences (Kassakian et al., 2011); and promoting regional coordination (Oseni and Pollitt, 2016).

1.1.2 Transmission investment

This section briefly summarizes the before and after effects of restructuring on transmission investment and draws attention to the upcoming global energy trends from a transmission investment perspective and points out the knowledge gap today.

Prior to restructuring, central planners of a state planned the transmission investment activity along with the generation activity. The transmission has acted as the highway for delivering electrical energy between the generation and the load. Traditionally, it was designed to meet the expected demand in the future within a market or a country. The main rationale for transmission investment was: technical reliability and economic efficiency, which has resulted in an overcapacity or lumpiness (Joskow et al., 2008). Transmission investment decisions were primarily based on matching the demand (load) with generation requirements to maintain the system reliability (Joskow et al., 2008).

After restructuring, with the development of privately owned power generators and the wholesale trading had caused transmission capacity to be used efficiently not only between the utilities but also between regions as well. Although this has caused stress in the already aging transmission infrastructure, it has helped the wholesale markets to become more liquid via transferring large bulks of power between regions (Pfeifenberger, 2012).

During that period, transmission investment has suffered from a long lag of investment into the markets due to its monopolistic feature (Joskow and Tirole, 2005). This has also caused congestion line failures and then cascading errors of voltage and frequency stability problems. Many solutions have been developed to overcome the transmission investment hurdle ranging from fully merchant (market) based forms to fully regulated forms such as Financial Transmission Rights (FTR) and Physical Transmission Rights (PTR) (Pollitt, 2012a; Rosellón et al., 2011).

In this process, transmission have been thought of saving fuel from the supply mix, and generation capital, and more importantly complementary or substitutable as indicated by Lévêque (2007). It also improves the system reliability and potentially removes or mitigates market power. But it has always been a difficult task to assess the cost/benefit measures of the investment process (Joskow et al., 2008). Therefore, economic benefits and technical reliability parameters only helped during the regulated period. However, during the deregulated phase many projects were canceled or mothballed.

One of the factors affecting the transmission investment process is also the bottom-up nature of the planning step. It has been studied in the literature extensively by concentrating on economic benefits and equilibrium models which may not have helped with the real transmission investment problem that is faced today. What has missed in those models was small scale, transmission planning conducted by utilities not considering regional integration (Lévêque, 2007).

Transmission development has had difficulty attracting private sector investment primarily because it is viewed as a public good similar to a highway. There are a few transmission projects built by the private sector and they rely on FTR as the basis for a business case. Our goal in developing the REH concept is to show that transmission can bring a higher option value to an investor, and the hub concept of transmission integrated with diverse generation across boundaries among many seen above, then this would be an advancement of the principle of flexibility coupled to economic value.

Currently, decision-making process for transmission investments is still heavily influenced by the monopolistic nature of the transmission system infrastructure. The dichotomy arises from a deregulation effort that was primarily confined to the generation and distribution of the regulated utility assets, but transmission system ownership remained as a regulated monopoly and this, in turn, caused transmission investments to lag behind the generation investment (i.e., centralized transmission planning versus decentralized generation investments) (Pfeifenberger, 2012). Although several options ranging from pure merchant to fully regulated options were developed to incentivize investments, the transmission system could not keep up with the demand and new emerging generation capacity with increasing share of renewable generation with variable and intermittent output on the system. Transmission investments initially flourished in the electricity markets in several countries (e.g., United Kingdom UK, United States US, Norway, Sweden) led by a few TSO (e.g., National Grid, Pennsylvania-New Jersey-Maryland PJM, Stattnet, Swenska kraftnat, respectively), but further developments of the wholesale markets have not been robust with the consequences that congestion is notable, the investment and integration pathways are unclear and regional capacity planning issues among the markets and as the regions are emerging (Ramachandra, 2009).

1.2 Research Problem Definition

Global energy trends pushing the electricity sector toward a low-carbon energy economy will require:

- integrating the geographically distributed (onshore or offshore) of new renewable energy resources,
- considering of the effect of climate change on the electricity markets,
- taking into account the changing hydrological conditions,

- adding of the new demand growth, distributed generation capacity investments, and
- capacity to absorb energy shocks through development global and/or regionally responsive systems that are integrated and minimizing market interdependencies of electricity and gas products.

There is a need for a radically new approach to reconsider the transmission investment from different perspectives so that it can effectively support the transition to a low-carbon energy economy. One approach to address the challenge through consideration of transmission investments as part of a "Regional Electricity Hub" concept.

All the above-mentioned challenges, as well as convergence with the climate change policy constraints, particularly the effect of climate change on electricity markets as argued by Mideksa and Kallbekken (2010) can be overcome by a novel (top-down) approach to transmission investment strategy in the evolving organized electricity markets and energy policy requirements. Besides providing engineering reliability and facilitating economic trade as the two primary objectives of transmission investments (Conejo et al., 2016), we propose the concept of a REH that integrates key geopolitical, economic, environmental and financial factors to foster investment decisions for transmission adequacy. A REH enabled through requisite transmission capacity becomes an investment option for regional optimization of diverse supply resource needs to come into play from similar concepts introduced earlier (FERC, 2011; OFGEM, 2010; EC, 2015). We argue that transmission has a positive and increasing role in the evolving convergence of climate change policies as they relate to connected markets, integration of large amounts of renewable generation and removal of congestion bottlenecks in the system. The goal is to optimize underutilized generation capacities over a wide geographic area through additional transmission interconnectors and to assess the benefits from a regional perspective that would support a low-carbon energy economy across several independent jurisdictions and countries (Aguado, Quintana, Madrigal, and Rosehart, 2004; EPRI, 2014; Baritaud and Volk, 2014; Newbery, Strbac, and Viehoff, 2016; IEA, 2016; Oseni and Pollitt, 2016; Boffa and Sapio, 2015).

In this context, REH is a transmission investment model to provide key insights to the policymakers in achieving a low-carbon energy transition regionally. Therefore, we build upon the existing body of knowledge on transmission investment approaches to help clarify the convergence of two high-level policy goals: energy policy as an integral part of climate change mitigation and adaptation strategies. The REH approach has the potential to provide key insights on how the transmission investments and effective pathways for enhanced electricity trade can pave the way for a broader decarbonization strategy at a lower cost to all consumers. The REH Framework can serve as a platform to:

1. identify the need for further investigation into adaptation strategies such as transmission planning, generation expansion (i.e., renewables), demand side response, or storage. However, the purpose of this study is not to investigate these adaptation strategies individually, which is already studied extensively, but

2. capture and consider them from a regional perspective, so that transition to low-carbon energy economy is effective.

1.3 Motivation, Approach and Objectives of the Research

The motivation of this research is to identify regional electricity hub strategies required for future flexibility of the organized energy markets and countries in answering common challenges such as:

- reducing the overall GHG emissions for a geographic region,
- utilizing idle energy within the region to compensate for the growing demand,
- providing generation flexibility across the region,
- providing increased reliability of the system,
- increasing energy trading among countries to increase overall social welfare,
- connecting - transmission, pipeline, or a LNG terminal,
- nudging investors more towards non-GHG polluting technologies, and
- creating a regional electricity hub that serves the region.

Therefore, overall thesis approach is based on:

- capturing global institutional energy knowledge gathered through platforms such as: conventions, world trade agreements, energy exchanges, or markets in answering common challenges stated above, and
- advancing this knowledge by applying standard operation research and financial option methods.

Then, the research objective is to originate ways to answer the motivation by utilizing the global institutional knowledge to:

1. develop a definition of the concept of REH to allow the need for transmission investments be better identified and tested against a full set of considerations that include the geopolitical, financial, environmental and economic perspectives (i.e., the REH parameters),
2. develop a framework for identifying the REH and the key parameters so that the benefits for the region are better ascertained and measured,
3. develop a generic mathematical model based on (1) and (2) above, and to apply this model to the evaluation of a case study for developing markets, Romania-Turkey transmission investment,
4. quantify benefits for the defined region according to the REH parameters,
5. utilize the application of REH Framework for developed markets, PJM, and
6. create a tool for identification of flexible assets serving the climate change objectives bringing policy makers, developers, and investors together to explore climate resilient asset opportunities from a regional perspective.

1.4 Overview of the Thesis

As outlined in Section 1.1, there are two overarching long-term energy policy requirements for the global energy sector:

1. enabling the transition to low-carbon energy economy, and,

2. evolving global electricity markets to support a range of cost-effective technological options at a regional level beyond the confines and constraints of one jurisdiction or country.

In this work as seen in Figure 1.1, we highlight a strategic energy policy view to addressing these long-term challenges by introducing a Regional Electricity Hub concept.

Figure 1.1 illustrates a strategic view of energy policy considerations and requirements for a typical asset investment cycle in an electricity market in any country with a typical timeline planning, construction and operation of these assets for optimal outcomes. These development cycles are based on similar standards across jurisdictions that address the requirements of resource adequacy, reliability, and flexibility including approaches to capacity options. The general schematic is a characterization appropriate for developing or developed markets. This investment cycle is usually determined at the individual corporate or country level.

However, when a group of countries in a contiguous geographical region as seen in Figure 1.1 can operate through an integrated enabling market with a long view (i.e., beyond ten years and longer), we see an opportunity for new value creation and cost-effective transition to a low-carbon energy economy by considering capacity options from a regional perspective.

REH Framework enables neighbouring countries integrated through markets to invest in common interest assets (such as an interconnector) bringing to practical realization the most capable options for a region. This type of "common interest" but market driven asset development cycle can be achieved by developing and developed markets.

Therefore, this thesis details the REH Framework and is organized as follows: Chapter 2 introduces the Regional Electricity Hub Framework and its major components: major parameters, indicators, and developing and developed market case studies. Chapter 3 reviews and details the REH Framework application process to developing markets to form a REH, Chapter 4 reviews and details the framework to developed markets to interconnect a REH, and Chapter 5 concludes with energy policy implications of geopolitics and finance with a future research direction related to the REH Framework.

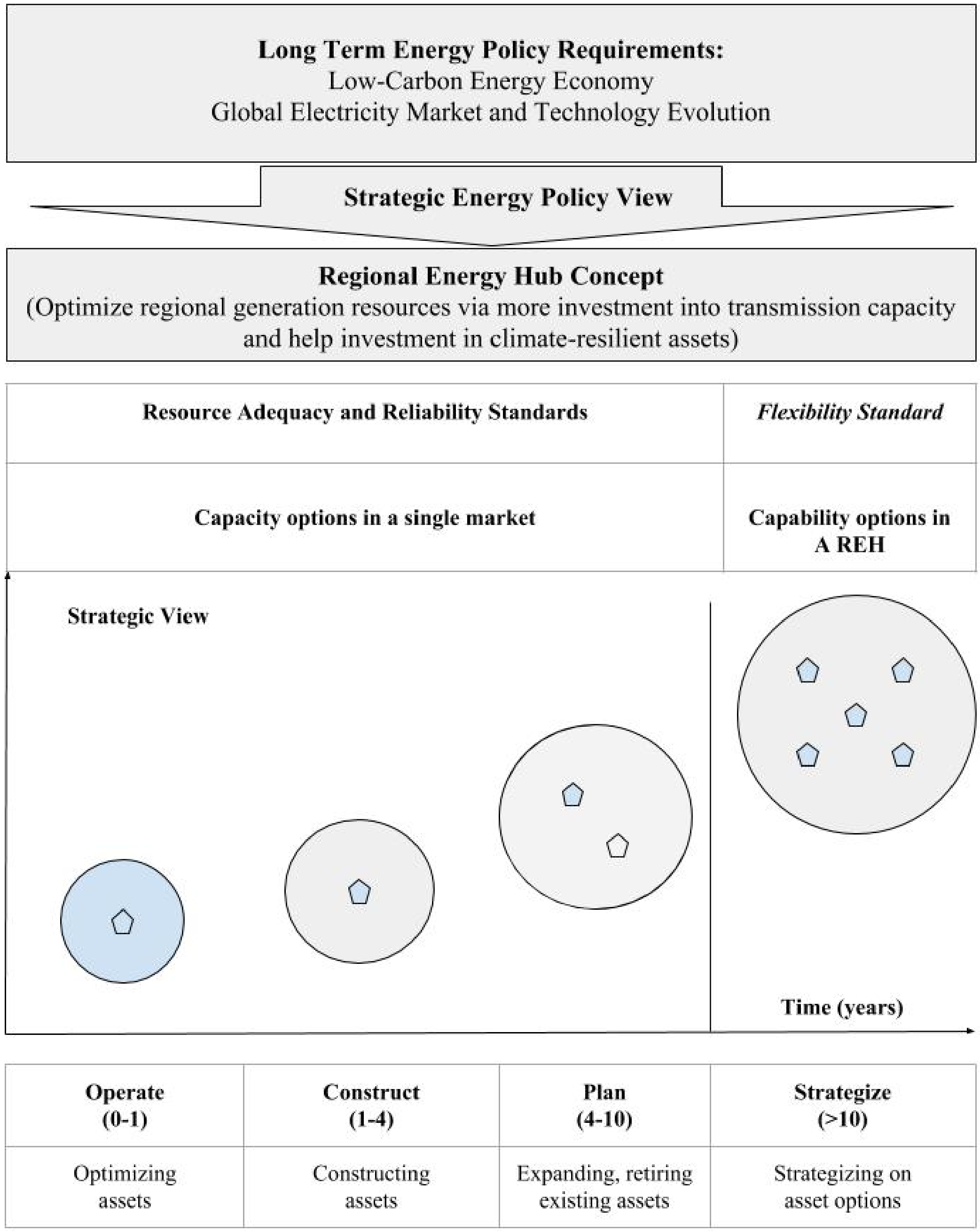

Figure 1.1: Strategic Energy Policy View: Markets' Evolution to Capability Options

1.5 Thesis Contributions

1. The development and definition of a ”regional energy hub” to support the basis for transmission investments,

2. A standardized energy policy tool for decision makers’ utilization at a regional level in transition towards a low-carbon energy economy,

3. The REH Framework and the analytical methods supporting the framework offers an innovative policy advance for evaluation of the readiness and capability of countries in reaching their targets and goals for a low-carbon energy economy exploiting the full benefits of regional integration. Being part of a Regional Electricity Hub offers a country the option to accelerate its decisions towards becoming a less carbon intensive economy at a lower cost, and

4. The REH Framework and the supporting tools and method can be applied as a platform in testing the feasibility of a transmission investment strategy to selected regions around the world.

1.6 Chapter 1: Summary

1. In light of the Paris Agreement, countries now around the world need to transit towards low carbon energy economy states while accounting for the country based - energy policy and evolving electricity market requirements, which alltogether establish the requirements for tomorrow.

2. There are many options as to how to reach to those targets. However, when we look

from a long-term strategic energy policy perspective, one option could provide wide and deeper decarbonization at the regional scale.

3. We propose a REH concept: optimizing regional generation sources via more transmission investment into transmission capacity and help invest in climate-resilient assets, so that transition towards low-carbon energy economy is effective.

Chapter 2

Method

2.1 Why Regional Electricity Hub?

2.1.1 Rationale

There are many useful attempts around the world towards creating a REH concept, but the framework and the parameters are not clarified for the hub or the region (Kassakian et al., 2011; Joskow et al., 2008; Bower, 2002). Many examples have been already moving in that direction, but without an appropriate definition for the REH. For instance, it is one of the European Union's objectives to create a single energy market by integrating regional electricity initiatives (Puka and Szulecki, 2014; Dimitrova et al., 2016; ECF, 2010). Another study examines the use of Canada's clean electricity exports as a route to a better energy strategy for North American region (Nathwani, 2013). Tabors (2009) also shows the economics of change before and after connection in the Gulf Countries Council region, while Al-Asaad (2009) points out the creation of regional electricity markets. Gadonneix et al.

(2008) argue that energy crises that have significantly dented economic growth in several Latin American countries could have been relieved if there had been adequate capacity and cooperation in the regional energy system. For South-East European region, Bajs (2003) studies the importance of the regional transmission system planning. Koritarov et al. (2004) investigate the economic and financial implications of regional electricity interconnections in South-Eastern Europe. Udrea et al. (2014) examine the optimal configuration of transmission corridor among countries Moldova, Ukraine, and Romania. Khalfallah (2015) discusses that "A super grid connecting the two shores of the Mediterranean where it could help Europe meet its targets for integrating renewable energy." Kravtsov (2009) points out that the Central Asian countries Kazakhstan, Afghanistan, Uzbekistan are part of the Central Asia Regional Economic Cooperation Program, where transmission investments can link these countries in delivering electricity. Musaba et al. (2006) discuss the Southern African Development Community where the region is endured with a lot of power generation potential, and integrated transmission expansion is the essential next step in bringing the economic efficiency to the region. Rana and Karmacharya (2014) points out that developing Nepal from land-locked state to a land-linked state would connect it with India by the cross-border transmission link. Chattopadhyay and Fernando (2011) argue that the improving cross-border trade by expanding on more transmission capacities in South East Asia would have economic, environmental and reliability benefits that can be captured under a new regulatory framework. Finally, Armar (2009) discusses creating regional power pools as a how to kit. Many examples could be extended to include in the aforementioned regional attempts.

It is clear that there have been many attempts in defining a framework for REH as outlined above. However, a generic framework would facilitate the investment process required for transmission expansion and hence, deliver the benefits regionally for the common challenges faced today.

2.1.2 Approach

We have developed a hypothesis for inter-TSO transmission investment, where the investment is considered as strategic for all countries in the region rather than focusing purely on economic efficiency and reliability of the individual country (Joskow et al., 2008). Such strategic investments would also facilitate tactical investments (e.g., renewable energy investments) in these countries. Moreover, operational issues such as congestion within and neighboring markets can be relieved with additional transmission capacity. It would also allow large volumes of power exchange among countries.

In order to elaborate on what is discussed above, Figure 1.1 and Figure 2.1 show three hypothetical countries/TSOs within the same region, but politically separated from each other. In Figure 2.1 on the left, these countries are not physically interconnected, whereas on the right side of Figure 2.1 they are interconnected by transmission lines.

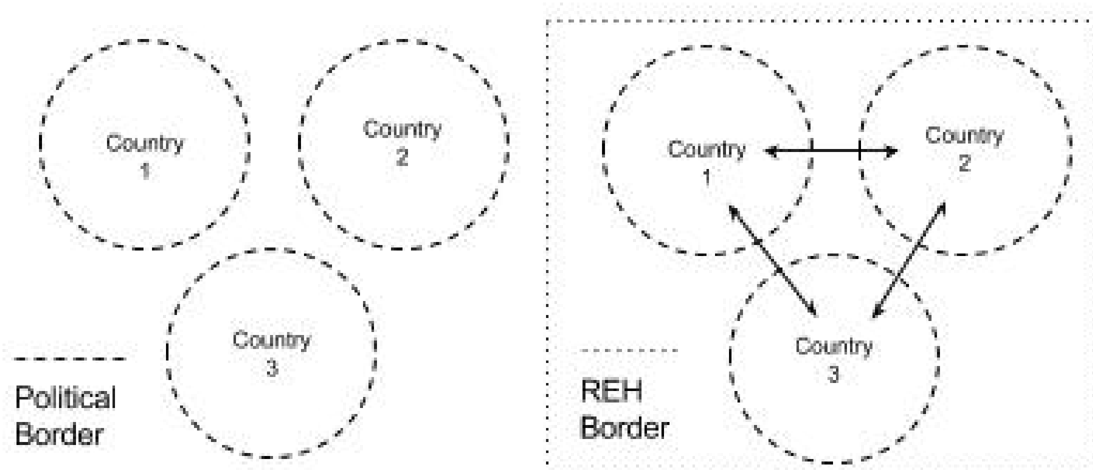

Figure 2.1: REH Concept: not connected (left) versus connected (right)

It is assumed that each country in Figure 2.1 has their unique fuel mix and demand characteristics, where country 1 with a clean fuel mix (i.e., there are no GHG emissions for its electricity generation within its political boundary), country 2 with a dirty fuel mix (i.e., substantial emissions exist for its fuel mix), and country 3 with a partially clean fuel mix (i.e., some clean and some dirty) fuel mix. Also, assume that all countries have unique seasonal and fluctuating demands.

Through this hypothetical example, it can be noted that the left side of Figure 2.1 would not lead to a low-carbon energy economy neither on a country basis nor within the same region. When countries 1, 2, and 3 are not interconnected, fuel mixes used for electricity generation in each country is not optimized to reduce their emissions. However, the right side of Figure 2.1 may lead to a low-carbon energy economy either on a country basis or within the same region. When these countries are interconnected, overall emissions of the region can be minimized by using available and cleaner fuel mix of any country. Therefore, interconnected countries may be in a position to optimize their fuel mixes, since they rely on a common interest project in the same region as well as they strive for a low-carbon energy economy. Such a common interest project (e.g., interconnector or transmission investment) also provides generation flexibility, reduced GHG emissions, and access to renewables as described earlier. In this context, REH is a geographic area where the boundaries of the countries are not defined by the political borders, but defined by the potential electrical energy resources as shown in Figure 2.1, in which all countries of the hub can jointly sustain. Hence, the REH hypothesis is that if the neighboring countries with mutually beneficial fuel mixes have common electricity market challenges and a common interest project such as a transmission investment, they can cooperate by considering the REH factors and then there can be a case for these countries to consider this transmission investment in transition to low-carbon energy economy. Consequently, we define "low-carbon energy economy" as the reduction of GHG emissions in a country's fuel mix.

In conclusion, we argue that transmission investment is one of the enablers that acts as a substitute or complementary to generation investments (i.e., substitute for dirty fuel generation investments and complementary to clean fuel generation investments) and facilitates the solutions for the short-term (e.g., energy trading) to long-term (e.g., climate change) problems.

2.1.3 Benefits

Chang et al. (2013) and Frayer et al. (2018) indicate that today's transmission investment realities need to take into account all the short to long-term benefits as well as regional considerations to extract the real value of the transmission investment shown in the hypothetical example. One particular method that estimates the benefits among many transmission expansion projects by a cooperative game - Aumann-Shapley approach is provided by Banez-Chicharro et al. (2017). From that perspective, we propose a top-down REH approach where the most common benefits such as increased reliability, decreased transmission congestion, integrated renewables, reduced losses, reduced resource adequacy requirements, increased connection, and increased competition in power markets are included and more importantly, idle capacities are regionally optimized towards a low-carbon energy economy. In this research, a REH Framework for transmission investment is proposed that can provide the following major benefits:

1. geographic: (i) increased connectivity, (ii) increased competition and consequently financial liquidity, (iii) flexibility for energy trading where common interests of countries are accounted in an integrated manner, and (iv) mitigation of weather and load uncertainty.

2. economic: (i) lower costs and consequently lower prices, (ii) generation flexibility by region's complementary fuel mix (different country fuel mixes to be pooled as a regional energy fuel mix) meeting peak consumption, and allowing access to lower cost generation, (iii) utilization of idle generation capacity within a region to compensate for the growing demand, (iv) substitution of capacities across generation and transmission facilities, (v) increased employment, increased economic activity, and (vi) reduced congestion due to improvements in transmission capacity.

3. environmental: (i) lower carbon-footprint in a region and mitigation of air pollutant emissions, (ii) enabling integration of renewable energy sources and distributed generation, (iii) exchanging for the cleaner form of electricity generation.

4. financial: (i) filtering the best investment alternative, and (ii) cost/ benefit analyses.

2.2 REH Framework

REH Framework, developed by Guler et al. (2018), is designed around four parameters: geopolitical, economic, environmental, and financial. Geopolitical parameter allows countries, markets, provinces to form broader alliances, and essentially, nudges them to rely more on trading than isolation among themselves. Additionally, the parameter rests upon four indicators (i) international economics, (ii) climate change with respect to transnational energy policies, (iii) seamless energy markets, (iv) energy market regulations to capture the global energy sector related to institutional knowledge. Geopolitical parameter enables REHs to be formed for a region's benefits developing out of these indicators. Economic parameter on the other hand optimizes the power generation capacities of mutually beneficial fuel mixes of this newly formed REH, resulting for the cost reduction for the region. Environmental parameter optimizes the region's emissions rather than nation's emissions, which effectively helps management of carbon reductions to be able to meet the Paris agreement commitments. Finally, financial parameter ultimately optimizes and potentially mobilizes resources towards a common interest project. Hence, the REH Framework manages the transition towards a low-carbon energy economy for the interest of energy policy makers, investors, and for the public.

Although REH Framework has two major parts as seen in Figure 1.1: indicators and parameters, the material effect of the REH Framework, however, is best seen in its application in case studies. We think that case studies best represents the evolution of markets from developing to developed markets perspectives. For a market to be considered as a developed market, it needs to have a liquid physical as well as a financial market to show the direction of the evolution of the markets. Therefore, two types of case are studied to best represent what may be available as potential scenarios globally : (i) developing electricity markets where we assume that markets have recently been restructured and there is enough evidence for a functioning physical market where geopolitical parameter in forming of REHs will be the starting point in the framework, (ii) developed electricity markets where we assume that markets have been restructured and there is enough evidence for a functioning physical market where financial parameter in interconnecting of REHs will be the starting point in the framework. Figure 2.2 shows the REH Framework detailed as follows:

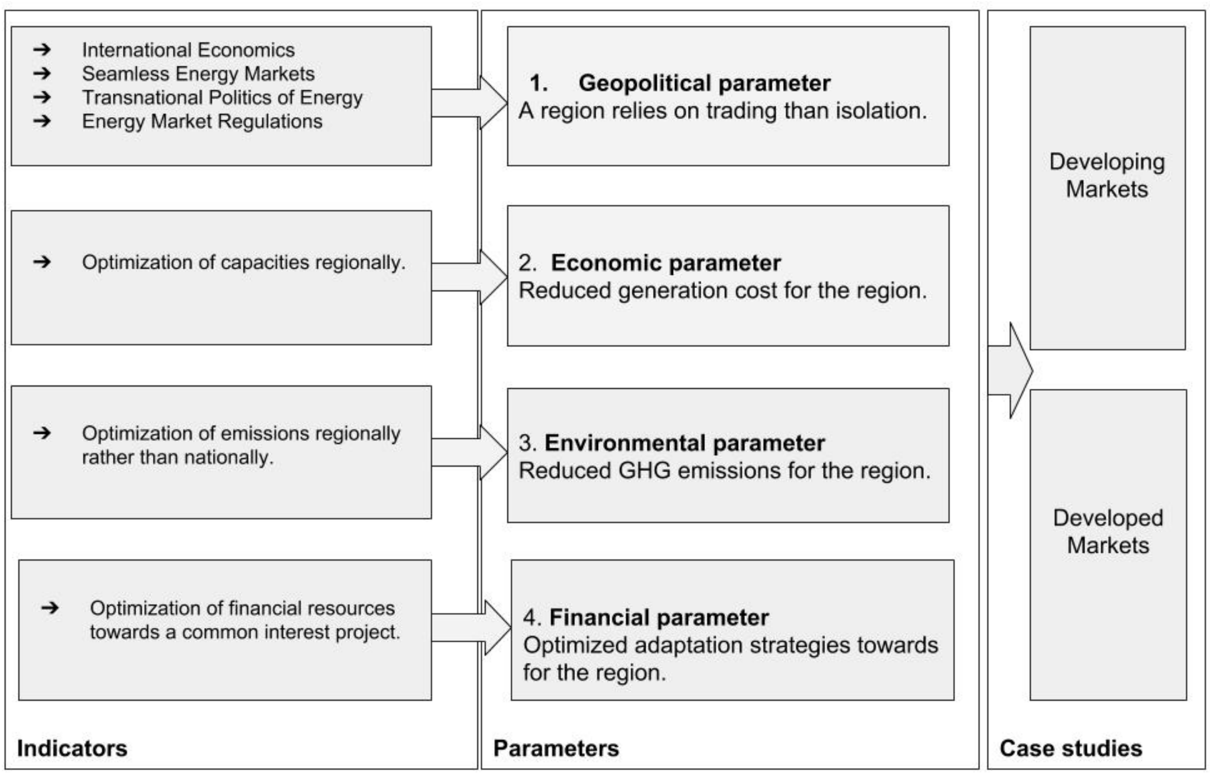

Figure 2.2: The REH Framework

2.2.1 Geopolitical parameter

The geopolitical parameter represents a broader alliance of countries, states or provinces where countries are geographically close or in different jurisdictions, but ultimately rely on trading rather than isolation. With the geopolitical parameter as an enabler, these countries or TSOs can benefit from increased trading in the same region where trading capacity is limited by existing interconnection (i.e., transmission) among the countries. However, today's energy geopolitics has been historically considered competitive/extractive in nature and mostly results in zero-sum games among the players, which may even halt trading among players in the long run (Austvik and Rzayeva, 2017).

Therefore, we propose that if geopolitics can be utilized to create a cooperative and inclusive field in the energy realm by utilizing the existing global institutional knowledge (deposited in agreements, platforms, connections, and exchanges) to identify REH countries, the transition to a low-carbon energy economy would be more effective. We think that the global institutional knowledge has enough evidence in place to support this cooperation. Hence, investments in common projects, such as transmission investment, could be accelerated, which would result in further slowing down of the climate change effects. For this reason, we have developed a geopolitical parameter pertinent to the energy realm based on four drivers where it best represents the global institutional knowledge, and where we believe the most cooperation could occur in the optimization of a region's energy resources. These are (i) international economics, (ii) climate change with respect to transnational energy policies, (iii) seamless energy markets, and (iv) energy market regulations. Moreover, specific indicators can be developed out of these four fundamental drivers which would help forming a REH effectively.

International Economics

With international trade barriers removed after the Second World War, goods and services have been traded across the borders around the world. The capital has followed the same suit and has financed the international trade since Bretton Woods IMF (2017). With the globalization effect during the 1990s, this move has helped shape the markets, trade patterns, and financing needs around the world. In fact, General Agreement on Tariffs and Trade (GATT) and World Trade Agreement have born in 1948 and evolved into World Trade Organization (WTO) in 1995 (WTO, 2017b).

In that sense, Weber and Peters (2009) argue that "trade presents challenges to climate policy through carbon leakage and competitiveness concerns, but also potential solutions through the use of cooperative trade agreements, technology transfer, or carbon tariffs against recalcitrant nations". Therefore, we argue that institutional knowledge regarding international economics from international trade and finance perspectives are further developed since the 1970s and can be utilized to develop indicators for energy markets. In our study, we have adapted these indicators that show the range and direction of trade relationship. On the one hand, the range can represent the existence of political union trade agreements or regional trade agreements, and on the other hand, it can indicate research studies advancing these regional trade agreements. We think that international economics is an externality that can be internalized while forming a REH.

Climate change with respect to transnational energy policies

United Nation's Framework Convention on Climate Change (UNFCCC) is one of the global institutional knowledge base that helps combat climate change by limiting average temperature increases. It has several essential parts. The convention, signed by 197 countries, is indicating that climate change and its adverse effects are well known by the parties. The Kyoto Agreement (the second part, which entered into effect in 1997 and signed by 192 countries) indicates that the signing parties agreed upon the emission reduction targets that are legally binding. The Paris Agreement (adopted in 2015 and ratified by 152 countries so far) also indicates that the convention's aim to accelerate and intensify the actions and investment needed for a sustainable low carbon future." The convention's institutional knowledge can be further developed for indicators to be used in energy markets. See UNFCCC (2017) for detailed information.

Similar to international economics, we have adapted indicators for a country advancing towards a low-carbon energy economy. In this case, the range can represent being a party to the convention or, on the other hand, being a party to the Paris Agreement. In this context, Keohane and Victor (2013) have argued that "the structure of international cooperation on some energy problems, such as climate change, is prone to deadlock. But by recrafting these problems usually by making them "smaller" and focusing on the areas where national interests are better aligned for international cooperation participating countries can avoid an impasse". Therefore, in this research, we propose that climate change effects could be best attacked by investing in common challenges (i.e., national interests) regionally rather than nationally. In this case, the number of countries involved in that specific common project would be determined by the geopolitical parameter.

Seamless energy markets

Electricity markets around the world have liberalized, progressed and gathered institutional knowledge in the form of day-ahead, futures/ forward, options or capacity markets. However, as the renewables deployment into electricity markets has increased, it has required a geographic coverage to obtain the least cost generation output out of the available energy sources. Particularly, without enough available capacity, transmission investment has lagged the generation expansion plans as it was originally designed for reliability, but not for the efficient use of resources in a region. Therefore, general electricity market challenges mentioned in Chapter 1 as well as in IEA (2016) need to be integrated systematically and regionally towards seamless operations as argued by Baritaud and Volk (2014) and Boffa and Sapio (2015).

Similar to indicators of climate change policies along with transnational energy policies, we have adapted indicators that would best reflect the direction of the development in the electricity markets, whether liberalization efforts take place in a specific country or there is an operational futures/forward market. An important issue, in this case, is that if there is an improving bilateral agreement in a trade relationship formed between parties, there is a possibility for building cross-border connectors as argued by Fischhendler et al. (2016). Also, if the trade has resulted in mistrust, then it is possible that investment in transmission may not be implemented. In order to capture this perspective, we have included additional indicators showing whether there is already an investment plan for a connector in place or not.

Energy market regulations

We have not adopted any indicators to reflect the institutional knowledge on market regulations as these are usually country specific. However, we argue that energy market regulations covering transparency platforms, financial regulations (whether physical or financial trades) and the role of institutions should be at least similar. More importantly, policies covering optimization of resources and actions on climate change should be inline regionally, but this is not the scope of this research.

Essentially, the geopolitical parameter narrows down to an identification of countries that can form a regional electricity hub to allow the quantitative determination of the cost minimization and emission reductions through a model to show the benefits of transmission capacity.

In this research, this is performed through utilization of the indicators born out of aforementioned four drivers of the geopolitical parameter. Detailed representation of these indicators will be depicted in the first case study.

Hence, the geopolitical parameter is the first step in a feasibility assessment of additional transmission capacity that can utilize and optimize the energy resources of the whole region while promoting a low-carbon energy future.

2.2.2 Economic parameter

This parameter optimizes capacities of mutually beneficial fuel mix and demand characteristics of countries, states or provinces, regionally and ultimately leads to regional power generation cost reduction reflected in the corresponding functioning electricity markets.

2.2.3 Environmental parameter

This parameter optimizes emissions of mutually beneficial fuel mixes of countries, states or provinces regionally and ultimately leads to a regional emission reduction.

2.2.4 Financial parameter

This parameter optimizes financial resources towards a common interest project by comparing with uncommon ones in a regional setting, and ultimately leads to optimized adaptation strategies towards a low-carbon energy economy for the region.

Once the corresponding REH is selected and evaluated, a common interest project for the REH can be achieved. Overall net benefit from these REH factors would lead to an investment decision while unlocking the region's potential as a REH. In this context, we propose a formal definition of REH as follows:

Regional energy hub is an intersection point of all energy (electricity) supply and demand routes geographically originating, transiting, ending (centralizing) in a pre-defined region where there is an ultimate net benefit for that region from the following perspectives: geopolitical, environmental, economic, and financial. When the net benefit is evaluated (e.g., it is positive), there is a need for a transmission investment for that region.

The final REH Framework is presented in Table 2.1.

Table 2.1: The REH Framework: parameters, indicators, indicator lists, and objectives

Overarching Climate Change & Global Electricity Market Requirements Leading to Low-Carbon Energy Economy			
1. Geopolitical (broader alliance of countries, states or provinces towards low-carbon energy economy in a regional setting)	International Economics, Seamless Energy Markets, Climate Change with respect to Transnational Politics of Energy, Energy Market Regulations.	A list of indicators enabling the selection of countries leading to a formation of REH countries.	A region relies on trading than isolation.
2. Economic (use of mutually beneficial fuel mix and demand characteristics of countries, states or provinces in a regional setting)	Optimization of capacities regionally.	A list of functioning day-ahead electricity markets for the REH formed.	Reduced generation cost for the region.
3. Environmental (use of mutually beneficial fuel mixes of countries: dirty versus clean resources in a regional setting)	Optimization of emissions regionally rather than nationally.	A list of installed capacities in the REH formed.	Reduced GHG emissions for the region.
4. Financial (compare common interest projects with uncommon ones in a regional setting)	Optimization of financial resources towards a common interest project.	A list of projects with corresponding, IRR, NPV, ROA values in the REH formed.	Optimized adaptation strategies towards a low-carbon energy economy for the region.

2.3 Chapter 2: Summary

1. Regional electricity hub as a concept has been explored sporadically in various parts of the world with a non-standardized approach.

2. To further develop the REH concept, we studied a wide range of planning concepts, practices and research approximately 18-20 studies - from around the world to identify key underlying theme and indicators of energy markets, optimization of capacities and emissions regionally.

3. Then, through the synthesis of these indicators, we developed REH parameters: geopolitical, economic, environmental, and financial. These are the core of the framework. However, no framework is complete without verification of these parameters in case studies.

4. Then, considering the different phases of development of electricity markets around the world, we streamed our case studies into two: developing or developed markets.

Chapter 3

Case Study 1: Forming a REH in developing markets: Romania - Turkey Interconnector

3.1 Overview

A recent study regarding a subsea cable between Romania (RO) and Turkey (TR) had been completed by Guler et al. (2013). This project has been rejected due to economic unfeasibility, i.e., only considering market price differences between the two countries. In this case, the transmission investment was only evaluated based on the benefits of the strategic interconnection capability between the countries and the arbitrage opportunities arising from price differences between the markets (Newbery et al., 2016). However, it could have arisen as a common interest project to support the transition to a low-carbon energy economy in the region. In the context that transmission may complement generation (Lévêque, 2007), this transmission investment project could have been implemented and it might have replaced a coal power plant investment planned in the region. Then, the transmission project would not only be able to mitigate emissions (or decrease carbon costs), but also more interconnection could have enabled the utilization of the idle capacity in the region, hence resulting further trading. Moreover, it could have also enabled the optimization of the regional electrical energy sources where transmission could be a substitute for generation sources (Lévêque, 2007; Hooper and Medvedev, 2009).

As developed by Guler et al. (2013), Tables 3.1 and 3.2 show the REH Framework applied to four countries: Bulgaria (BG), Greece (GR), RO and TR, i.e., the REH Countries. In this case study, TR and RO subsea interconnector is considered as a common interest project, which was found unfeasible due to the previous investment selection method (i.e., only based on market price differentials).

Table 3.1 shows the geopolitical parameter indicators developed in Chapter 2 and they are evaluated for the aforementioned countries with a simple grading system (e.g., 0 or 1 point). The objective of this grading is to indicate/gauge the REH readiness such that the hypothetical REH countries shown in Figure 3.1 would have same or closer grade points. With this method, we think that the geopolitical parameter table can be universally applied for developing potential REH(s) around the world. Table 3.1 gives the details on the evidences for the REH in question as follows.

From an international economics point of view, indicators show evidence of a potential regional trade agreement benefiting REH countries, particularly Greece and Turkey, as argued by Kocaslan et al. (2014). Hence, one point is given to each country indicating the existence of a regional study. Also, WTO publishes a list of regional trade agreements among REH countries in their corresponding database (WTO, 2017a). In this case, one point is given to each country, since there is a bilateral or a regional economic integration agreement (e.g., European Union) in place among the REH countries.

Table 3.1: REH case study: select a set of countries to form a REH

1. Geopolitical Parameter: Which countries could benefit from the increasing trading?		Evidence Required	BG	TR	GR	RO
International Economics	1. Is there an indication of increased economic welfare after forming a regional trade agreement?	Existence of a study or negotiations under way. (0 or 1 point)	1	1	1	1
	2. Party to any trade agreement?	Existence of a WTO based or Regional economic integration organization (i.e. EU, NAFTA) agreement in place. (0 or 1 point)	1	1	1	1
Climate Change Policies with respect to Transnational Politics of Energy	3. Party to UNFCCC?	Annex I. 1 Non-Annex I. 0 (0 or 1 point)	1	1	1	1
	4. Ratified the Paris Agreement?	Yes. 1 No. 0 (0 or 1 point)	1	0	1	1
Seamless Markets	5. Is there a liberalization of electricity market act or an operating financial market in place? (any applicable one)	Any, 1; Non, 0.	1	1	1	1
	6. Is there a liberalization of gas market act or an operating financial market in place? (any applicable one)	Any, 1; Non, 0.	1	1	1	1
	7. Electricity- Interconnector?	Any, 1; Non, 0.	1	1	1	0
	8. Gas - Interconnector?	Any, 1; Non, 0.	1	1	1	0
Common Project(s)	9. List any common project being considered but not undertaken yet?	Any, 1; Non, 0.	0	0	0	1
Geopolitical Parameter - Outcome	10. Outcome		8	7	8	7

Table 3.2: REH case study 1: select a set of countries to form a REH

2. Economic Parameter. Do these countries have functioning electricity markets (intra-day, day-ahead markets) that could reflect increase in social welfare or decrease in generation costs? BG - Independent Bulgarian Energy Exchange, IBEX GR - Operator of Electricity Market - LAGIE RO - Romanian Gas and Electricity Market Operator, OPCOM TR - Energy Exchange Istanbul, EXIST
3. Environmental Parameter. Do these countries have fuel mixes that are beneficial to eliminate emissions environmentally? Table 3.3 shows region's clean energy fuel mix vs. dirty one. 53,024 out of 120,378 MW total installed capacity is clean energy.
4. Financial Parameter. Do these countries have a portfolio of common interests that need to be invested in financially? TR-RO Transmission Investment.

From the climate policies perspective, indicators show evidence related to the UNFCCC participation indicated by one point in the table as well as one point for ratification information related to the Paris (2018) Agreement. From the seamless markets point of view, a list of energy (power and gas) exchanges in REH countries is published at the Association of European Energy Exchanges member website given in Europex (2017). We have graded the existence for each electricity and gas markets as one point.

Furthermore, evidence showing existence of a physical electricity interconnection can be found at European Network of Transmission System Operators for Electricity (ENTSO-E) transparency platform under cross-border transmission flows at the border-country level (ENTSO-E-TP, 2017a). Accordingly, we have graded the existence of a connection from/to each country as one point regardless of the number of lines. Therefore, each BG-TR, TR-GR, GR-BG, and RO-BG connections are given one point, whereas each RO-TR and RO-GR connections are given zero point.

Similarly, evidence showing existence of a physical gas interconnection can be found at European Network of Transmission System Operators for Gas (ENTSO-G) transparency platform under cross-border transmission flows at the border-country level (ENTSO-G-TP, 2017). Similar to grading for electricity connections, we have graded one point for each BG-TR, TR-GR, GR-BG and RO-BG connections, whereas zero point is given to each RO-TR and RO-GR connections.

Table 3.2 shows the economic, environmental, and financial parameters applied to the REH countries formed in Table 3.1. For further clarification, the economic parameter regarding the existence of a functioning electricity market given in Table 3.1 is not repeated here. It merely shows that the countries have already developed their markets.

In the subsequent sections, a mathematical framework for this REH case study is developed.

3.2 Mathematical Model

In Figure 3.1, the transmission line connections between the countries of the REH are displayed and each node (i.e., bus) represents a country in the REH (i.e., there is no detailed representation of countries' transmission systems). Power imports/exports of the countries from/to other countries outside of the REH are not considered, but it can be easily incorporated into the model. Although financial constraints are not modeled at this stage of the study, the role of financial constraints, i.e., debt, is central in structuring such major infrastructure projects. As Tverberg (2015) discusses, inability to originate financial resources for energy projects could create significant problems in energy supply security.

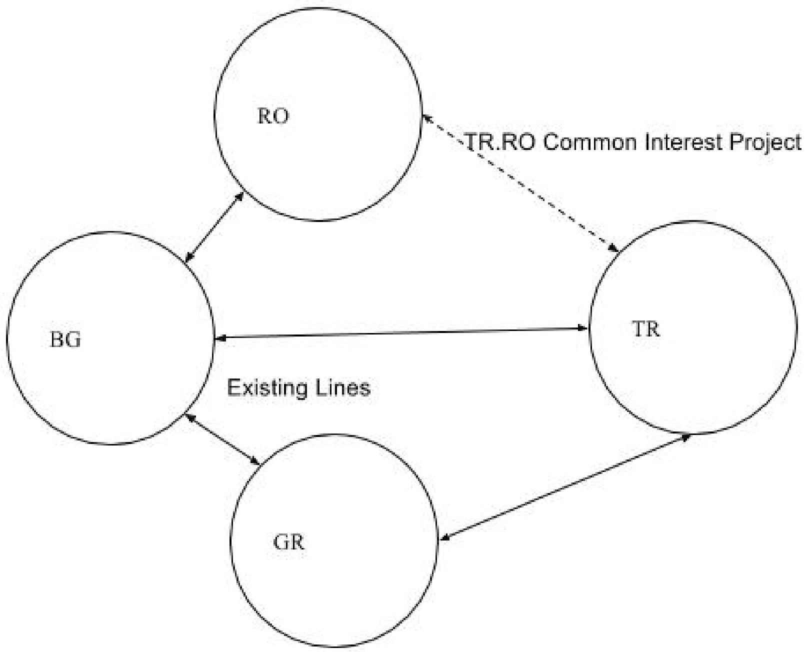

Figure 3.1: REH Case Study for Developing Markets: Bulgaria, Greece, Romania, and Turkey

Sets and indices

- $i \in N$ set of buses (countries): BG, TR, GR, RO

- $j \in N_i$ set of buses connected to bus i

- $h \in H$ set of generation technologies: nuclear, coal, hydro, gas, renewables

- $m \in M$ set of time blocks: peak, intermediate, base

Parameters

- c_h^G Cost of generation by technology h, \$/MWh

- $c_h^{CO_2}$ Cost of emissions by generation technology h, \$/MWh

- d_{mi} Demand at each bus i for time block m , hundred MW

- B_{ij} Susceptance of each transmission line connecting buses i and j, per unit (p.u.)

- $f_{ij}^{min}, f_{ij}^{max}$ Minimum and maximum of flow limits on transmission line connecting buses i and j, hundred MW

- g_{ih}^{max} Maximum power output of generation technology h at bus i , hundred MW

Variables

- g_{ih} Generation by technology h at bus i , hundred MW

- θ_i, θ_j Bus angle at buses i and j, radian

- γ Dual variable for reference bus constraint

- $\rho_{ij}^{min}, \rho_{ij}^{max}$ Dual variables for flow limit constraints

- λ_i Dual variable for energy balance at each bus i (i.e., nodal price), \$/MWh

- ϕ_{ih}^{max} Dual variable for maximum generation output constraint

The mathematical notation and the model for the REH Framework are as follows:

$$\min_{g_i \theta_i} \sum_{i \in N} \sum_{h \in H} (c_h^G + c_h^{CO_2}) g_{ih} \tag{3.1}$$

subject to

$$\sum_{h \in H} g_{ih} - d_{mi} = \sum_{j \in N_i} B_{ij}(\theta_i - \theta_j) \qquad \lambda_i \qquad \forall i \in N \quad and \quad m \in M \tag{3.2}$$

$$-f_{ij}^{min} \leq B_{ij}(\theta_i - \theta_j) \leq f_{ij}^{max} \qquad \rho_{ij}^m in, \rho_{ij}^m ax \qquad \forall i \in N \quad and \quad j \in N_i \tag{3.3}$$

$$\theta_{GR} = 0 \qquad \gamma \qquad \text{reference bus} \tag{3.4}$$

$$g_{ih} \leq g_{ih}^{max} \qquad \phi_{ih}^{max} \qquad \forall i \in N \quad and \quad h \in H \tag{3.5}$$

$$g_{ih} \geq 0 \qquad \forall i \in N \quad and \quad h \in H \tag{3.6}$$

$$-\pi \leq \theta_i \leq \pi \qquad \forall i \in N \tag{3.7}$$

The objective function (3.1) of this model minimizes the total of the generation and emission costs. Constraints (3.2) is the energy balance at each bus where the dual variables represent the electricity prices at each bus and constraints (3.3) are the power flow limits through transmission lines, where flows are modeled according to the linear Direct Current (DC) flow assumptions for simplicity and tractability (Gabriel et al., 2012). Constraint (3.4) defines the reference bus as GR and constraints (3.5) are for the maximum power outputs for each generation technology and country. Finally, non-negativity constraints for generation are modeled by constraints (3.6), and bus angle limits are represented by (3.7). Clearly, the model is a Linear Programming (LP) problem that can be solved very easily using the state of the art LP solvers (e.g., CPLEX in GAMS (2015)).

As described in Chapter 2, utilizing REH approach for novel transmission investment strategies could reduce countries' carbon emissions. It can facilitate the integration of renewables and also release congestions. To better assess the impact of transmission investment between Romania and Turkey, we have discretized the load-duration curves using several demand blocks. We have modeled the yearly demand, by three load blocks (denoted by m) using the base, intermediate (mid) and peak hours of a typical load-duration curve at bus i. Baseload is a permanent load and is generally supplied by nuclear and coal power generation. Intermediate and peak loads are the average and maximum loads, respectively, and are usually satisfied by flexible power generation such as gas and hydro.

3.3 Assumptions

Traditionally, transmission investment assessment studies are conducted for a target year, e.g., using target year's load-duration curve or its approximation (Kazempour, 2013). In our REH approach, instead of a target year load-duration curve, we have utilized a discretized load- duration curve for each bus in the recent year to assess for the transmission investment feasibility. We have done this to see whether a regional electricity trading opportunity could have been enabled by a potential transmission investment for the REH in question or not. The use of this model for realistic purposes would require careful forecasts for both generation and demand in the target year. In Figure 3.2, a typical annual load-duration curve is depicted, and it is discretized by using three-time blocks (peak, intermediate, and base). We assume that peak, intermediate (mid) and base loads appear, 20 percent, 35 percent, and 45 percent, respectively, of total hours in a year (i.e., 8,760 h). This corresponds to 1,752 peak load hours 3,066 intermediate load hours and 3,942 baseload hours. Consequently, we have assumed the following load factors: 1.0 (peak), 0.70 (intermediate), and 0.50 (base).

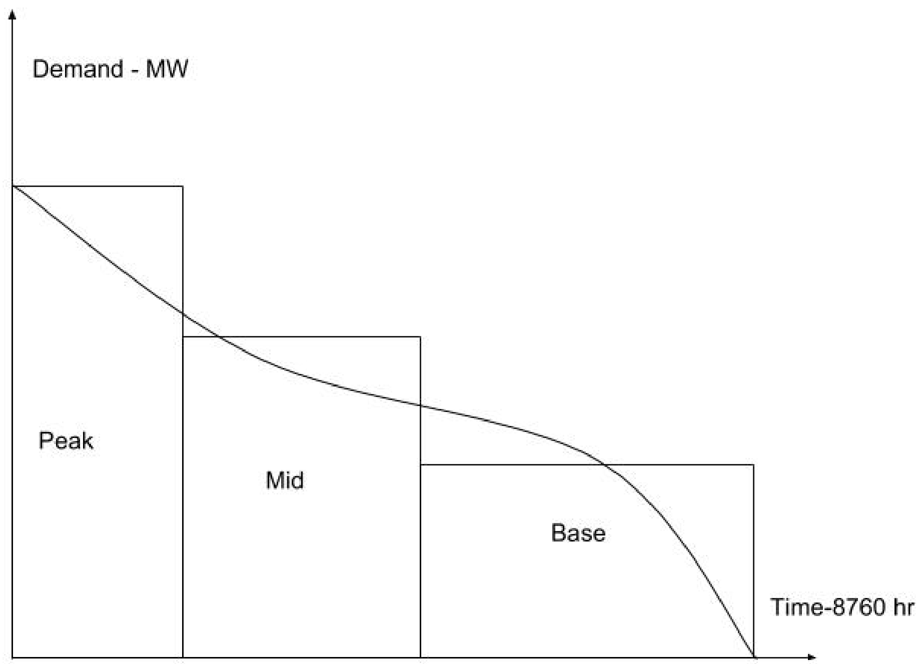

Figure 3.2: Discretized load-duration curve

3.4 Data Set

The model concentrates on the generation and emission cost minimization of the REH countries selected. Table 3.3 presents the breakdown of the REH countries' installed capacity by generation technology in 2015 (ENTSO-E-TP, 2017b). It also shows the peak demand values for Bulgaria, Greece, Romania (EUMarkets, 2014) and Turkey (TEIAS, 2015). Table 3.4 shows the marginal generation and emission costs of the installed capacity per technology assumed for this study (IEA, 2010), and our assumptions on capacity factors from a long-term system planning perspective. Finally, Table 3.5 presents the data related to the transmission system (ENTSO-E-TP, 2017a; Gabriel et al., 2012).

Table 3.3: REH installed capacity (MW) and peak demand (MW)

REH Capacity	Nuclear	Coal	Hydro	Gas	Renewable	Total	Peak Demand
BG	2,000	5,648	2,965	19	653	11,285	7,967
TR	-	15,226	23,664	25,643	4,345	68,878	41,002
GR	-	4,459	3,149	5,631	4,386	17,625	9,894
RO	1,298	5,872	6,470	4,861	4,089	22,590	8,627
REH (Total)	3,298	31,205	36,248	36,154	13,473	120,378	67,490

Table 3.4: Transmission line parameters

Line #	From	To	Susceptance - B_{ij} (Siemens)	Capacity (MW)
1	BG	TR	1,000	500
2	BG	GR	1,250	800
3	TR	GR	1,500	500
4	BG	RO	1,500	500
5	TR	RO	1,500	500

Table 3.5: REH generation parameters per technology

REH	Nuclear	Coal	Hydro	Gas	Renewable
Generation Cost ($/MWh)	24	25	6	65	22
CO_2 Cost ($/MWh)	0	24	0	11	0
Peak capacity factor	0.80	0.50	0.75	0.65	0.35
Mid capacity factor	0.85	0.75	0.45	0.40	0.25
Base capacity factor	0.95	0.75	0.25	0.10	0

3.5 Results and Discussion

The LP models for different demand blocks are solved using CPLEX under GAMS (2015) on a Windows-based personal computer with a processor at 2.4 GHz and 8 GB of RAM. The transmission investment simulated between RO and TR resulted in a cost-effective fuel mix switching among REH countries. This ultimately reduced generation costs and emissions for these countries because low cost/emission generation technologies are utilized. Table 3.6 presents the results of power flows among REH countries before and after transmission investment.

It can be observed that in base- and mid-load blocks, there are net power flows from Romania to Turkey in the amount of 500 MW. On the other hand, there is a net power flow of 59 MW from Turkey to Romania in the peak load block. Note that negative values in Table 3.6 depict the power flows in reverse direction and these flows are governed by the Kirchhoff's Laws of current and voltage. In the peak demand case, the Kirchhoff's laws do not allow any net flows from RO to TR, but from TR to RO only. Hence, this reduces the generation of coal plants by 59 MW. In the peak demand case, the feasibility of the solution is satisfied by higher generation/emission costs.

The dual variable for the power flow constraints (e.g., ρ_{ij}^{min} or ρ_{ij}^{max} depending on the flow direction) shows the value of the unit MW increase in the new transmission line capacity (i.e., the marginal value of transmission line capacity). It is found to be \$53/hour for both base- and mid-load demand blocks, where the full capacity of the new RO-TR line is used. In the peak demand case, as the capacity of the line is not fully utilized, it is zero. A future extension of this study may consider the capacity size of the new transmission line as a decision variable in the model, where the model also determines optimal capacity size. But this would require a new modeling approach, i.e., an equilibrium model, which is out of the scope of this study and left for future research.

Table 3.7 presents *the net* change in fuel mix *(installed capacity)* of each REH country (after minus before transmission investment), complying with the objective of the REH model, e.g., minimizing generation costs and emissions for the overall region. Note that there are only changes in capacity utilization of coal and gas generation, whereas there was no change in the capacity utilization of nuclear, hydro, and renewable generation. This suggests that the new transmission line between Turkey and Romania exchanges fossil-fuel based gas generation with cheaper coal generation. This has reduced not only the costs of generation but also the emissions with the flexibility enabled by the new transmission capacity. Table 3.8 shows the associated cost and emission reductions as a result of this fuel switching.

For the peak-load block, hourly generation and emission cost figures have increased by 3,149 \$/hour. On the other hand, for the base- and mid-load blocks, hourly generation, and emission cost figures have decreased by 26,500 \$/hour and 35,559 \$/hour, respectively. Additionally, overall annual cost savings can be estimated from these figures using the number of hours per load block:

$$(26,837 * 3,942) + (20,000 * 3,066) - (2,376 * 1,752) \approx 160\, Million\, \$/year \tag{3.8}$$

It should be noted that new transmission investment among REH countries would reduce power generation costs and emissions. Also, the REH method can integrate countries in such a way that transmission investment would create ultimate benefits for each REH country.

Table 3.6: REH power flows before and after transmission investment based on discretized load-duration curve ("-": 0%, "NA": not applicable)

REH Power Flows		BG-TR	BG-GR	TR-GR	BG-RO	RO-TR
Peak	Before (MW)	-442	-136	500	-500	-
	After (MW)	-373	-205	313	-500	-59
	Change	-16%	51%	-37%	-	NA
Mid	Before (MW)	500	800	210	500	-
	After (MW)	500	800	210	250	500
	Change	-	-	-	-50%	NA
Base	Before (MW)	500	541	-101	500	-
	After (MW)	500	712	104	250	500
	Change	-	32%	-203%	-50%	NA

Table 3.7: Change in REH capacity utilization (after *minus* before transmission investment in MW, percent changes in parentheses)

REH Capacity Change		Coal	Gas
Peak	BG	0	0
	TR	0	-197 (-1%)
	GR	0	256 (8%)
	RO	-59 (-3%)	0
Mid	BG	-250 (-6%)	0
	TR	0	-500 (-10%)
	GR	0	0
	RO	750 (149%)	0
Base	BG	-79 (-3%)	0
	TR	0	-295 (-11%)
	GR	0	-376 (-100%)
	RO	750 (78%)	0

Table 3.8: REH costs (before and after transmission investment)

REH Cost ($/hour)		Generation	CO_2	Total
Peak	Before	1,893,075	602,672	2,495,747
	After	1,895,451	603,445	2,498,896
	Difference	2,376	772	3,149
	Change	0.13%	0.13%	0.13%
Mid	Before	1,070,841	341,451	1,412,292
	After	1,050,841	334,951	1,385,792
	Difference	-20,000	-6,500	-26,500
	Change	-1.87%	-1.90%	-1.88%
Base	Before	785,927	275,273	1,061,200
	After	759,090	266,551	1,025,641
	Difference	-26,837	-8,722	-35,559
	Change	-3.41%	-3.17%	-3.35%

3.6 Case Study 1: Sensitivity Analyses

Utilizing different sources of data sets after forming a REH and analyzing it by a mathematical model shown in equation 3.1 have generated a need to conduct sensitivity analyses for some of the model parameters used in the case study 1. The sensitivity analyses have been performed for major model parameters such as: generation plus CO_2 costs as well as peak demand values for countries. The results below shows that the optimal solution is unchanged, i.e., where TR-RO interconnector is beneficial.

Table 3.9 shows three time blocks of base, intermediate (mid) and peak as well as the corresponding demand values ranging between lower (LO) and upper (UP) limits for the assumptions discussed in section 3.3

Table 3.9: REH case study 1: a country's peak demand parameter limits (MW)

Upper	Base		Mid		Peak		
Lower	LO	UP	LO	UP	LO	UP	Current
BG	1,179	5,415	1,647	5,883	7,339	8,180	7,967
TR	18,231	20,795	23,944	34,201	26,136	42,804	41,002
GR	3,839	5,141	6,867	9,120	8,870	10,150	9,894
RO	2,600	7,004	4,787	9,191	6,881	9,817	8,627

Similarly, Table 3.10 shows three time blocks and the corresponding per unit generation plus CO_2 cost parameter values ranging between lower (LO) and upper (UP) limits for the cost assumptions discussed in Table 3.4.

Table 3.10: REH case study 1: per unit generation plus CO_2 cost parameter limits ($/MWh)

Generation Technologies		Base LO	Base UP	Mid LO	Mid UP	Peak LO	Peak UP
BG	Nuclear	-inf	36	-inf	36	-inf	136
BG	Coal	24	64	24	57	-inf	136
BG	Hydro	-inf	36	-inf	36	-inf	136
BG	Gas	36	inf	36	inf	-inf	136
BG	Renewable	-inf	36	-inf	36	-inf	136
TR	Nuclear	-inf	89	-inf	89	-inf	89
TR	Coal	-inf	89	-inf	89	-inf	89
TR	Hydro	-inf	89	-inf	89	-inf	89
TR	Gas	36	133	67	133	73	inf
TR	Renewable	-inf	89	-inf	89	-inf	89
GR	Nuclear	-inf	64	-inf	89	-inf	110
GR	Coal	-inf	64	-inf	89	-inf	110
GR	Hydro	-inf	64	-inf	89	-inf	110
GR	Gas	64	inf	64	124	-inf	110
GR	Renewable	-inf	64	-inf	89	-inf	110
RO	Nuclear	-inf	36	-inf	36	-inf	36
RO	Coal	24	62	24	62	24	89
RO	Hydro	-inf	36	-inf	36	-inf	36
RO	Gas	36	inf	36	inf	36	inf
RO	Renewable	-inf	36	-inf	36	-inf	36

On the other hand, Table 3.11 displays three time blocks and the corresponding generation capacity values ranging between lower (LO) and upper (UP) limits, for the installed capacity assumptions discussed in Table 3.3.

The sensitivity results have shown that the optimal solution that enables TR-RO interconnector is robust, particularly for each countries' peak demand values, total generation plus CO_2 costs, and generation capacities. Moreover, we have also presented sensitivity analyses for transmission line limit parameters for case study 1 in Appendix C, where robustness of the results are, again, validated.

Table 3.11: REH case study 1: generation capacity limits (MW)

Gmax		Offpeak		Mid		Peak	
		LO	UP	LO	UP	LO	UP
BG	Nuclear	467	4,703	1,393	5,629	1,386	2,227
BG	Coal	2,803	inf	3,929	inf	2,610	3,451
BG	Hydro	0	3,545	1,027	5,263	2,010	2,850
BG	Gas	0	inf	0	inf	0	639
BG	Renewable	0	2,803	0	4,092	14	855
TR	Nuclear	0	2,269	0	4,756	0	14,685
TR	Coal	11,124	13,688	5,919	16,176	5,810	22,478
TR	Hydro	5,621	8,185	5,148	15,405	15,945	32,613
TR	Gas	2,269	inf	4,756	inf	14,685	inf
TR	Renewable	0	2,269	0	5,843	0	16,386
GR	Nuclear	0	1,107	0	58	0	1,113
GR	Coal	3,149	4,451	1,149	3,402	1,973	3,343
GR	Hydro	592	1,894	0	1,475	2,105	3,475
GR	Gas	0	inf	58	inf	3,403	4,774
GR	Renewable	0	1,107	0	1,154	1,278	2,649
RO	Nuclear	0	2,956	0	2,355	0	2,783
RO	Coal	1,712	inf	1,251	inf	1,745	inf
RO	Hydro	0	3,330	0	4,163	3,662	6,598
RO	Gas	0	inf	0	inf	0	inf
RO	Renewable	0	1,712	0	2,274	240	3,716

3.7 Chapter 3: Summary

1. For the first case study, we have first started off by applying the geopolitical parameter of the REH Framework to form a REH. The geopolitical parameter enables countries for further trading by application of institutional knowledge present for the region. Hence we have asked the question: which countries could benefit from increased trading. Indicators such as international economics, climate change agreements, transnational politics of energy, seamless markets and common projects along with the questionnaires provide a basis of knowledge and evidence for establishing the requirements leading towards a common interest project within a regional electricity hub. The result is that these four countries could form a REH.

2. Now, we have formed a REH in South-Eastern Europe with a TR-RO common interest project. The economic parameter optimizes newly formed REHs capacity. Before proceeding, we have shown evidence for the following question: is there evidence that these countries can individually reduce their cost in their corresponding indicators? Then, the environmental parameter optimizes newly formed REHs capacity. Before proceeding, we have shown evidence for the following question: do we have evidence in place that these countries have mutually beneficial supply mixes?. Then, the financial parameter optimizes resources towards a common interest project.

3. Then, we have applied cost minimization for generation and emission for the newly formed REH to optimize the resources of the formed REH in reducing cost, measuring emissions, and quantifying financial resources saved before / after enabling an interconnector.

4. Then, we have applied cost minimization for generation and emission for the newly

formed REH in order to optimize the resources of the formed REH in reducing cost, measuring emissions, and quantifying financial resources saved before / after enabling an interconnector.

5. Results have shown that TR-RO Interconnector, enables power flow between the countries. As a result, enabled TR-RO Interconnector, changes the capacity utilization of each country away from fossil fuel utilization. Hence, the interconnector enables cost reduction and emission reduction for the defined region.

Chapter 4

Case Study 2: Interconnecting a REH in developed markets: PJM

4.1 Overview

Besides developing markets, such as the case study in Section 3, the REH Framework can be utilized by applying this innovative method for developed markets, such as the ones in North America. Developed markets include both liquid physical markets as well as financial transactions (futures, options, swaps operated by exchanges) as recently noted by PJM (2017) in its correspondence to the US House of Representatives. In this case study, we have assumed that PJM interconnection is a good example of a developed market, and hence, based on the REH Framework parameters, it is also a representative regional electricity hub.

The REH Framework financial parameter indicator represents an optimization of financial resources towards a common interest project as seen in Table 2.1, which is equally similar to the PJM capacity markets' representation of optimization of generation or demand resources based on a resource adequacy requirements as documented by The Brattle Group, Astrape Consulting (2013) for Federal Energy Regulatory Commission (FERC). Therefore, according to the REH Framework, we identify an opportunity to compare common interest projects (e.g., transmission investments) with uncommon ones (e.g., capacity markets) from a regional perspective. The REH Framework puts a light on transmission capacity opportunities regionally for a regional hub (or market, e.g., PJM) by utilizing its existing forward-looking capacity market. If the capacity market price shows the regional need for a generation resource by utilizing the REH Framework, this can be also used to indicate a potential recognition or a need for an interconnector capacity.

4.2 PJM is a Regional Electricity Hub

Pennsylvania and New Jersey had formed the world's first interconnection and continuing power pool in 1927 by amalgamating three utilities from these states based on sharing resources on the economic benefits of forming a market. Later on, by addition of two more utilities from Maryland formed PJM, making of the Pennsylvania-New Jersey-Maryland in 1956. Utilities continued joining in 1956, 1965 and 1981. In 1993, PJM became an independent entity when the PJM Interconnection Association was formed to administer the power pool. In 1997, PJM started administering bid-based day-ahead market as well as became the US's first ISO (i.e., an ISO operates but does not own transmission assets). Later in year 2002, PJM was designated as a RTO by the FERC in 2002 to operate the multi-state transmission projects in the states (PJM, 2018). Today, PJM, as part of the Eastern Interconnection, serves 13 states as well as District of Columbia with 165 GW of installed capacity that provides electricity for 65 million people. As PJM has developed towards a REH, the states and utilities explored efficiencies and benefits brought by interconnecting and sharing resources and joined an RTO (FERC, 2018b). Figure 4.1 shows RTOs in North America.

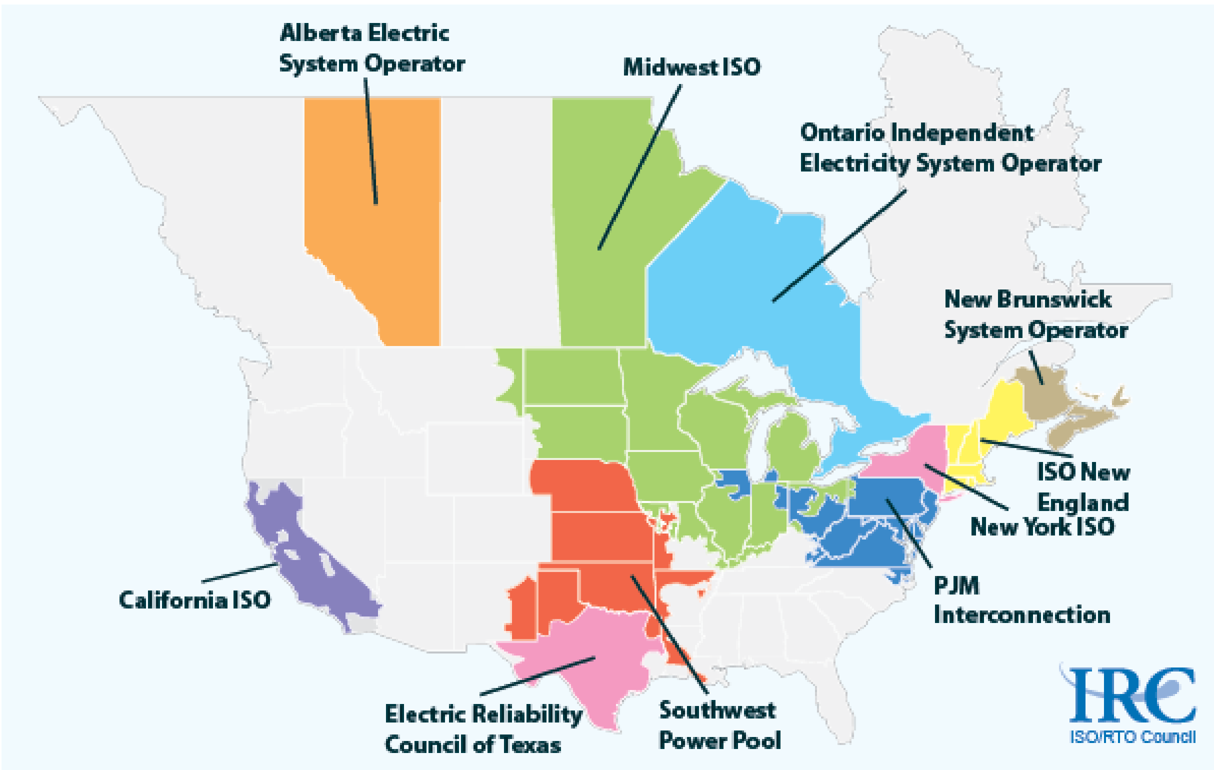

Figure 4.1: RTO Map in North America (Source: ISO RTO Council)

Briefly, when we apply the REH Framework and its associated parameters (geopolitical, economic, environmental and financial) to the PJM market, we see it evolving from developing to developed market today. Two fundamental parameters, geopolitical and economic had initially helped established this market and played an essential role in its expansion. Hence, aforementioned states formed the interconnection in 1927 in which the economic benefits to be reaped based on the purpose of dispatching a low-cost generation regionally.

We assumed that geopolitical benefits of resource sharing by a common interest project such as a transmission capacity had been sufficient enough as an objective at that time compared to today's objectives of transitioning to low-carbon energy economy according to the Paris Accord targets. In the REH Framework, we quantify the reduction targets as the environmental parameter within the framework that was not explicitly considered by PJM in early developments. Nevertheless, PJM has been an evolving and a functioning developed market with the addition of states to extend the geopolitical coverage of the region and by building additional transmission capacities. Throughout the years, to further enable the benefits and optimize resources regionally, transmission capacities have been built within PJM.

4.3 Capacity Options: Generation vs. Interconnector

Markets around the world value electricity in a day-ahead market where supply resources and demand-side meet to form prices. This has been a prominent method of valuing resources producing electricity since the 1980s with the transformative work of Schweppe et al. (2013). When energy-only markets clear based on prices formed, suppliers earn their revenue by selling electricity as a product and by providing ancillary services. When markets are not cleared either by demand inflexibility (i.e., unable to respond to prices) or by inelastic supply (due to costly electricity storage), blackouts could occur as discussed by Cramton et al. (2013) extensively. Therefore, energy-only markets allow prices to rise so high above the operating costs of resources that recovery of the cost of capital is possible to avoid possible blackouts.

In the US, ERCOT is the only energy market that allows this to happen where suppliers can recover capital costs of resources invested. For other markets, such as PJM and

California Independent System Operator (CAISO), wholesale electricity markets have price caps (mostly between $1,000 and $10,000 per MWh) that constrain how much sellers can make when supply is tight (Bushnell et al., 2017). Therefore, now it is argued that without this stream of income, it may not be profitable to build new capacity to meet demand in the future that can result in potential blackouts. The deferral or the missing money problem has been put into perspective with a comparison of 15 resource adequacy markets in Cramton and Stoft (2006).

In order to overcome this issue, developed markets (e.g., PJM) have designed and added capacity markets besides the energy-only one. In this capacity market, suppliers providing electricity to consumers have to procure enough resources to meet demand not only for the day-ahead market but also for the predicted demand (also known as variable resource requirements curve) in the future as well. Therefore, Reliability Pricing Model (RPM), a PJM capacity market, effectively ensures the grid reliability for the long-term (i.e., three years in PJM capacity market). As part of this process, participants must procure capacities to generate electricity or reduce demand three years into the future. PJM, through its RPM process, establishes a virtual resource requirement curve and determines a cost of new entry based on a generation resource (e.g., a gas-fired technology such as combined cycle or open cycle). Through the auctions in PJM capacity market, capacity prices are determined, and this process repeats itself annually.

These capacities may include new and existing generators, upgrades for existing generators, demand response (i.e., consumers reducing electricity use in exchange for payment), energy efficiency and transmission upgrades as per PJM. For transmission capacity upgrades, an offer made through the capacity market is referred to as Qualifying Transmission Upgrade (QTU) and it does not include newly build interconnectors. For an interconnector to be considered beyond the QTU, it needs to be part of the Regional Transmission

Expansion Planing (RTEP) where it takes into account load growth, changing the capacity mix, distributed energy sources and aging infrastructure with a 15-year planning horizon (PJM.RTEP, 2018).

Cepeda et al. (2009) had discussed the importance of regional coordination of adequacy policies to ensure long-term reliability for optimal choice between generation and interconnection. In that sense, PJM.RTEP (2018) oversees the system enhancement process from the reliability lenses while managing the inputs from public policy, resilience, capacity resources, market efficiency, interregional coordination, aging infrastructure, operational performance, transmission service, load forecast, and demand resources as detailed in PJM.RTEP (2018).

As an input to the RTEP process, the REH Framework can help improve utilization of capacity markets further as an early indicator to show the need for a capacity option as an interconnector in PJM. Hence, the RTEP process can be enhanced to monitor not only generation capacity but also interconnector capacity options for consideration in the long-term development on an annual basis. This approach would make the grid more reliable in terms of monitoring its options for flexibility, enabling capable capacities and alignment with the FERC definition of resilience, i.e., "The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event" (FERC, 2018a).

4.4 A Model for the REH Framework

Based on the earlier discussion about PJM as a REH in Section 4.1, we identify the REH Framework's financial parameter indicator as optimization of financial resources towards a common interest project and this can be best reflected in the PJM capacity markets. The

REH Framework through the financial parameter enables us to make a valid comparison of common interest project (e.g., interconnector capacity) with uncommon ones (e.g., generation capacity). Through this comparison, the REH Framework provides better insights into the operation of the capacity markets by allowing a clear delineation of the value of capacity as an option between a generation source and a transmission interconnector as an enabler of the capacity mechanism. Thereafter, the fundamental question would be as "which asset would be the better option, generation or transmission?", which is considered from a flexibility perspective by (Hogan, 2017). In this context, we argue that the capacity markets' three-year forward price could help us determine the best option among these assets.

4.4.1 Linking capacity markets parameters to financial option value determinants

The utilization of derivatives (or instruments such as futures, options or swaps) has been widely discussed and applied in electricity markets for risk management, valuation and optimization of operating assets as shown by many authors (Pineda and Conejo, 2012; Deng and Oren, 2006; Carmona and Durrleman, 2003; Liu and Wu, 2007). Utilities and investors have used these instruments to hedge against commodity fluctuations (as a fuel input) and volatile electricity day-ahead market prices to avoid jeopardizing operating assets' profitability. Application of these instruments on capacity markets, however, have mostly been on the generation adequacy and capacity payment mechanisms as discussed fairly by Vazquez et al. (2002) and Oren (2005), but not specifically on transmission as a potential regional option. In this respect, PJM's capacity markets could help decision and policy makers on recognizing or determining the most capable option between a generation or an interconnector capacity.

PJM, through its reliability pricing model, organizes capacity auctions every year, which sets the price for the region in the three-year forward planning horizon. Base residual auction planning period parameters such as target level of capacity and net cost of new entry for generation or other resources are published by PJM.RPM1 (2018) annually. Once the auction is completed, base residual auction results are published where it shows the cleared capacity market prices and capacities in PJM.RPM2 (2017). Out of this process, two key parameters emerge that could help determine the capable options: net cost of new entry for the auction and the capacity market prices cleared for the region.

Table 4.1: Linking capacity markets parameters to option value determinants

Determinants	Option Determinants	Capacity Market Parameters
S	Stock price	Capacity market price ($/MW- Day)
K	Exercise price	Net cost of new entry ($/MW- Day)
t	Time to expiration	Investment time horizon
r	Risk free rate of return	Risk free rate of return
Sigma	Variance of returns of stock price	Variance of returns of capacity market price

Table 4.1 shows an assumed link between the option value determinants, as infamously described by Black and Scholes (1973), to capacity market parameters where similar analogy has been presented by Haahtela (2012) and Fernandes et al. (2011) in relating financial options to real options. As argued by Lambrecht (2017) extensively, "a real option's underlying asset or payoff is often highly complex, not traded and subject to strategic interactions with its environment", and "hence causing real (projects or assets) options not to be traded in the market". This, in turn, as argued by Lambrecht (2017), causes "absent a market price". Therefore, we assume that the existence of a capacity market and price formation

in PJM enables to conclude a potential link between the option value determinants and capacity market parameters (see Table 4.1).

Accordingly, we assume that capacity market is the underlying asset and its price is formed in PJM's RPM similar to the stock price, S. RPM's capacity market price and its historical variance reflect the sigma, which is the variance of returns on a stock price. Exercise price, K, is similar to the net cost of new entry parameter. Now, this is an important assumption from capacity option perspective, since we assume that net cost of new entry could be either a generation or an interconnector cost. Life of the option is the same as the life of the project considered. Risk-free rate of return is the same as that could be applied in a capacity market.

4.4.2 Approach to valuation of capacity options

As shown by Black and Scholes (1973), John et al. (2006) and also depicted by Damodaran (2018) as "an option contract provides the holder with the right to buy or sell a specified quantity of an underlying asset at a fixed price at or before the expiration date of the option". There are two types of options: (i) call options (right to buy), and (ii) put options (right to sell). As Damodaran (2018) further details in the following: a call option gives the buyer of the option the right to buy the underlying asset at a fixed price (exercise price or K) at any time prior to the expiration date of the option. Moreover, Damodaran (2018) details further in the following: a put option gives the buyer of the option the right to sell the underlying asset at a fixed price at any time prior to the expiration date of the option. An option can be exercised any time prior to its expiration (i.e., an American option) or it can be exercised only at expiration (i.e., a European option).

As defined by John et al. (2006), option values are categorized as: (i) in-the-money,

(ii) at-the-money, (iii) or out-of-the money. Therefore, a call option is in-the-money when S>K, at-the-money when S=K, and out-of-the money when S<K. On the other hand, a put option is in-the-money when S<K, at-the-money when S=K, and out-of-the-money when S>K.

Any option, whether call or put, are exercised only when it is in-the-money. John et al. (2006) specifies that an in-the-money option will always be exercised on the expiration date if it has not been exercised previously. Moreover, John et al. (2006) defines the intrinsic value of an option as the maximum of zero and the value the option if it were exercised immediately. Hence,

- Call option's intrinsic value: Max (S-K,0)
- Put option's intrinsic value: Max (K-S, 0)

As argued by Newbery (2016), "whether or not interconnectors should be included in auctions is less important than that their contribution should be recognized in determining the procurement amount". Hence, we use this recognition as a starting point and argue that this could be achieved by determining the intrinsic option value between generator and interconnector projects by using historical and forward net cost of new entry as well as capacity market prices published by PJM.RPM1 (2018) and PJM.RPM2 (2017) against the net cost of new entry for interconnector projects.

Besides the intrinsic value, an option has a time value as well. And this is directly related to how much time, which an option has until it expires and associated the volatility of the underlying stock. As a result, the total option value is equal to its time value and its intrinsic value. The option parameters are shown in Table 4.1, such as volatility (Sigma), t (time to expiration), and r (interest rate) are used in option valuation (e.g., market price of an option). Black and Scholes (1973) option pricing formula is one way of calculating this among many. However, further research is required in using Black and Scholes (1973) application in capacity markets, particularly in capacity market price formation fundamentals as well as in volatility relation to REH Framework and its parameters.

In summary, the objective in linking option pricing theory to capacity markets is to differentiate and recognize the so-called in-the-money capacity options based on cost spreads of generation and interconnector projects by utilizing the intrinsic value of an option.

4.4.3 Data set

Different HVDC transmission interconnectors (a common interest project) currently operating and those expected to connect to PJM would provide a valid range of total investment costs for comparing an interconnector as a capacity option to a generation project. By further studying these projects from the REH Framework, we can verify our initial investigation on whether the PJM's capacity market inherently values interconnectors as a capacity mechanism on the same basis as a generator, or not.

We have selected the merchant HVDC projects (presented in Table 4.2) based on three rationale: (i) REH Framework: we have assumed that PJM is already a REH and it considers interconnecting with other neighboring markets, (ii) time span: we have particularly concentrated on projects in covering the operational time span of PJM's capacity markets, which has been officially in operation since 2007, and (iii) interconnectors: we have not selected any transmission projects within the PJM, where it would only contribute to releasing congestions rather than help connect with other markets. Therefore, our fundamental argument is to investigate whether PJM capacity markets intrinsically treats interconnector capacity as an option or not. This would help determine REH Framework's effectiveness in originating and identifying interconnector capacity options in a developed market such as PJM.

Based on the aforementioned requirements, Table 4.2 displays interconnector projects and their associated development and cost information. Total Investment Cost (TIC) figures have been discounted to daily equivalent values (using an annual interest rate of ten percent and a life-time of twenty years) denoted by net cost of new entry for an interconnector to compare them with the net cost of new entry for generation presented in Table 4.3. Some of the PJM's merchant transmission projects and detailed information can be found in PJM.MTP (2018).

All interconnector projects are unique due to different types of connections (e.g., underground, overhead, or submarine), distances, development risks and geographic locations that result in distinct TIC profiles. The selected interconnector projects are as follows:

- Neptune project is an operating 660 MW interconnector capacity by merchant investment that connects PJM to New York Independent System Operator (NYISO) in the USA with a total investment cost of 600 million $ (M$).
- Hudson project is an operating 660 MW interconnector capacity by merchant investment that connects PJM to NYISO with a total investment cost of 850 M$.
- Lake Erie project is a proposed 1,000 MW interconnector capacity by merchant investment that connects PJM to Independent Electricity System Operator (IESO) in Ontario, Canada with a total investment cost of 1,000 M$.
- Grain Belt Express Clean Line is a proposed 3,500 MW interconnector capacity by merchant investment that connects PJM to Southwest Power Pool (SPP) in the USA with a total investment cost of 2,300 M$.

- Eastern interconnector is a 1,300 MW interconnector capacity by merchant investment that connects PJM to MISO in the USA with a total investment cost of 200 M$. This is a hypothetical project recently referenced in Frayer et al. (2018) .

Table 4.2: Recent HVDC projects connecting to PJM

Projects	Neptune	Hudson	Eastern Interconnector	Grain Belt Express Clean Line	Lake Erie Interconnector
Status	Operating	Operating	Hypothetical	Proposed	Proposed
As of	2007	2013	2018	2019	2021
Hub	PJM to NYISO	PJM to NYISO	PJM to MISO	SPP to PJM	PJM to IESO
Type	Under + Submarine	Submarine	Overhead	Overhead	Submarine
Distance (mile)	65	65	45	780	73
Capacity (MW)	660	660	1,300	3,500	1,000
TIC (M$)	600	850	200	2,300	1,000
$/MW-Day	288	408	49	208	316

Table 4.3 presents the net cost of new entry for generation and the resulting capacity market prices retrieved from the corresponding auction year along with net cost of new entry for interconnectors. As it is shown in Table A.1 in Appendix A, there is no cor-

Table 4.3: Net cost of new entry cost for generation and transmission against capacity market prices

PJM RPM	Net Cost of New Entry				Capacity Market
	Generation	Transmission Hypothetical	Transmission Operating	Transmission Proposed	Prices
Three-Year Forward	\$/MW-Day	\$/MW-Day	\$/MW-Day	\$/MW-Day	\$/MW-Day
Averaged Cost & Prices	263.94	48.75	348.47	262.87	100.39

responding net cost of new entry for an interconnector for each auction year due to the development time of interconnectors. Therefore, to make consistent comparisons among net costs of new entry for generation and capacity market prices against different interconnector types (e.g., operating, proposed and hypothetical), we have utilized average values for the net costs of new entry for interconnectors as in Table 4.3.

4.4.4 Results and discussion

As in-the-money figures in Table 4.4 presents, HVDC projects deliver value against the generation capacity. This is not only evident in the hypothetical project, but also in the four other operating and proposed projects. This validates the type of recognition delivered by an interconnector as argued by Newbery (2016).

We have known that the potential discrepancy rising from the cost figures sets a challenge as well as an opportunity for the purpose of this research. Therefore, we recommend that ISOs and RTOs, as part of their RTEP process, should calculate merchant HVDC the net cost of new entry figures similar to net cost of new entry for generation and they should provide this information to the capacity market base residual planning for each year. Markets are evolving and flexibility needed by resiliency requirement of FERC is a prime example of markets as well as the grid. Earlier load matching with generation stood well with the technical requirements of electricity transmission. However, as markets evolve, transmission needs have to be considered in concert with generators' capacity additions for a determination of value to the system. The proposed REH Framework provides a solid basis for assessing interconnections with other REHs.

The REH Framework provides the cost of installed transmission capacity ranging from 49 to 350.00 \$/MW-Day or on average 220.03 \$/MW-Day, from simple overhead to submarine cables as shown in Table 4.3. The average interconnector cost is still lower than the RTO average generation capacity: 264.94 \$/MW-Day. Here, we employed intrinsic option value calculation method to compare cost figures of interconnector and generation against a capacity price. As the results show that PJM capacity market intrinsically values interconnector as a capacity option.

It is also possible to mention other benefits, such as the availability that transmission provides for other generation resources such as in the case of Lake Erie interconnector which provides access to Ontario's nuclear power generation fleet.

Table 4.4: Intrinsic value option comparison for the net cost of new entry between a generation and an interconnector

Intrinsic Option Value	Generation		Transmission Hypothetical		Transmission Operating		Transmission Proposed	
	Call	Put	Call	Put	Call	Put	Call	Put
	$/MW-Day	$/MW-Day	$/MW-Day	$/MW-Day	$/MW-Day	$/MW-Day	$/MW-Day	$/MW-Day
2007/2022 Average Figures	0.00	163.55	51.64	0.00	0.00	248.08	0.00	162.48

4.5 Chapter 4: Summary

1. In our previous case study 1, we have formed a REH by utilizing the geopolitical parameter, in case study 2 , we have utilized the REH Framework's financial parameter for an existing REH such as PJM to seek for capacity options so that further trading can be enabled.

2. Here, we have linked the financial option theory determinants to capacity market determinants of the PJM market to recognize, differentiate and value between a generation and an interconnector capacity option need in a developed market.

3. Then, we have picked five interconnectors to present the common interest part (interconnector) of the financial parameter of the REH Framework where we have utilized PJMs capacity market to present the uncommon interest (local generation). Here, we have employed intrinsic option value calculation method to compare cost figures of interconnector and generation against a capacity price.

4. Results show that PJM intrinsically values interconnector as a capacity option within its capacity market to interconnect with other neighboring markets.

Chapter 5

Conclusion

5.1 Overview

REH Framework, as an energy policy tool, enables countries in their respective geography to strategize energy and electricity market transitions towards a low-carbon energy economy by mobilizing financial resources more towards common interest projects. Two case studies presented in this thesis have shown that REH Framework is universally applicable for developing as well as developed markets and brings higher option value whether from financial or emission perspectives.

REH Framework through case studies showed that the fundamental difference between developing and developed markets is reflected in utilizing the framework by a range of countries from geopolitically different ones to financially integrated ones.

However, potential limitations for the REH Framework may exist (see section 5.3). But, the very core of the Framework facilitates and acts as a feasibility platform in bringing countries and markets together which allows transitioning towards a low-carbon energy economy.

Therefore, future research for the REH Framework should essentially concentrate on identifying potential hubs around the world by applying data-driven methods. This could be achieved by utilizing REH Framework's parameters and indicators in capturing the global energy institutional knowledge, consequently, resulting in ironing out specific adaptation strategies for each REH.

5.1.1 Case study 1

We have utilized a geopolitical parameter to select a set of countries to form a regional electricity hub. We have utilized the economic parameter to minimize cost and the environmental parameter to reduce CO_2 emissions simultaneously in the newly formed REH's total energy fuel mix. The results for TR-RO case study indicated that the total cost minimization approach for the region results in a net benefit in favor of the transmission investment. The REH enables transmission capacity to achieve reduced cost generation and emissions by physically interconnecting markets in a predefined region, essentially enabling fuel switching of carbon-based power generation. We have introduced a formal definition of the REH and presented a conceptual framework for the REH development including the underlying mathematical model.

5.1.2 Case study 2

We have utilized the financial parameter of the REH Framework for an existing REH such as PJM. Our case study showed that by investigating PJM's capacity market from the REH Framework's perspective, PJM intrinsically values transmission capacity within its capacity market. This is validated by HVDC interconnector investments in PJM that are currently operating or proposed. PJM has been operating as a regional electricity market operator and can be considered as a successful 'exemplary' REH that could serve as a model for newly formed REHs around the world. The REH Framework bridges an important gap between the capacity markets and the RTEP process such that the net cost of new entry figures for transmission could be developed alongside with the net cost of new entry for generation for other REHs around the world.

Development of such a database would make application of the REH Framework a highly effective policy instrument for enhancing the quality of decisions on transmission investments in support of a low-carbon energy future.

5.2 Energy Policy Implications: Geopolitics and Finance

We expect that given an investment time horizon of 5-10 years, a region should be able to identify and consider an adaptation strategy in their corresponding REH Framework. In our view, the framework will act as a platform to explore feasible options. Hence, we expect that transmission investment could be a key enabler of renewable energy, which will profit by accessing to transmission in remote locations where demand is not in proximity. In conclusion, REH Framework would be an important energy policy instrument to evaluate the readiness (or effectiveness) of countries in reaching low-carbon energy economy as a region collectively. Hence, it can also accelerate country's decision towards becoming less carbon-intensive by determining clear policy options among many. Therefore, we think this method can also be applied as a feasibility platform to selected regions around the world.

Tomorrow's grid will simply need to be highly capable and resilient to maneuver around short-term challenges arising from extreme weather events such as hurricanes, floods, storms and extreme heat. Moreover, it should meet the long-term challenge of greenhouse gas mitigation through effective optimization of the energy supply mix at the regional level. Enabling transmission investment and large-scale enhanced electricity trading among countries on a continent-wide basis is one part of the answer about whether to form a REH (and interconnect several REHs), or not. We expect that a clear stipulation and definition of a REH will play key roles in tomorrow's flexible grid and markets. Furthermore, the REH Framework for a region is a building block of truly interconnected global markets in leading to low-carbon energy transition.

Investment into climate-resilient assets is important for countries to transit to low-carbon energy economy. Long-term perspective in managing this transition rests with a vision of today's policy for the future. However, assets are facing the impasse imposed by two major parameters, geopolitics and finance, wherever they may be applicable around the world. Geopolitics is now a key parameter not only for carbon mitigation but also for renewable energy. Finance has never been so available yet not so accessible. So, the opportunity lies in treating these two parameters where they could most facilitate investment into common interest assets or projects. One global market for power where assets become geopolitically indifferent and financially available for global trade could even further help transitioning to low-carbon energy economies.

5.3 Limitations of the REH Framework

Below are some of the limitations for the implementation of the REH Framework.

REH Framework does not currently consider the technical aspects of how newly formed REH could operate and whether current electricity market structures need to be revisited or not. Therefore, as this is a strategic system planning tool, it does not take into account how technical challenges could be faced in the day-to-day operation of a REH.

REH Framework rests upon parameters where it enables further investment in transmission capacity for reducing country's reliance on fossil fuel-based power generation. There may be cases that REH Framework cannot allow further reduction of carbon emissions for some countries, because countries or markets may have already clean fuel mixes. However, then, REH Framework can still serve as a feasibility platform to study the flexibility of a REH.

Current economic dispatch model used in the case study 1 only considers forming a REH from a system planning perspective and does not include costs for other sources of emissions (SO_x, NO_x) and investments. However, the model is flexible enough to cover these issues in future research.

REH Framework currently formulates a geopolitical parameter from a perspective of accumulated institutional knowledge and it develops indicators in bringing countries/markets to form a REH. However, there may be cases that although rational formation of a REH would be evident, parties may opt not to form a REH. This could be due to political tensions that may exist among regional countries. Hence, further research in the influence of political issues on system planning is required.

5.4 Future Research

As for the future research, we plan to work on two general research streams. The first theme is the energy policy research based on a geopolitical framing of regional electricity hubs leading to optimization of resources of combined fuel mixes of in developing markets. We forecast that there will be 15-20 regional electricity hubs around the world that need to be studied from a geopolitical perspective. Secondly, we plan to develop financial engineering methods to value asset options in developed markets by benchmarking investments: transmission, renewables, gas, coal, nuclear, and storage in an investment horizon of 5-10 years. This is an important area of research where financialization of energy markets are taking shape around the markets today.

Finally, a research program based on the REH framework would be needed to further develop the concepts mentioned above. The following scope map shows some of the core elements of the program.

1. REH Development: Energy Policy

   - Identify and form REHs around the world based on a geopolitical parameter as utilized in case study 1 by employing a data driven approach to originate potential interconnector options for each REH, and run an economic dispatch model for each identified REH to quantify benefits based on REH Framework parameters before and after implementation of interconnectors. Identification and formation of REHs will enable future research perspectives in presenting potential energy transition strategies specific for each region.
   - Identify REHs around the world based on a financial parameter as utilized in case study 2 by employing a data driven approach to originate potential

interconnector options for each REH, and investigate by financial option theory whether each identified REH values interconnectors as part of their long term planning perspective or not.

2. REH Energy Technology Investment Alternatives: Financial Engineering of Options

   - Compare results found above in the energy policy section for each REH
   - List and value investment alternatives for each REH.
   - Publish results for each REH.
   - Study the effect of inter-REH behaviour.

3. REH Potential Funding Sources

   - United Nation's Sustainable Development Solutions Network
   - National Science Foundation - Innovations at the Nexus of Food, Energy and Water Systems
   - Natural Sciences and Engineering Research Council of Canada
   - International Energy Agency collaborative research projects.
   - World Bank through applications in its projects.

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APPENDICES

Appendix A

Net cost of new entry for generation and interconnector vs. capacity market prices

A.1 Net cost of new entry for generation and interconnector vs. capacity market prices

Table A.1: Net cost of new entry for generation and interconnector vs. capacity market prices

PJM RPM	Net Cost of New Entry				Capacity Market
Auction	Generation	Transmission Hypothetical	Transmission Operating	Transmission Proposed	Prices
Three -Year Forward	$/MW-Day	$/MW-Day	$/MW-Day	$/MW-Day	$/MW-Day
2021/2022	321.57			316.87	140.00
2020/2021	292.95				76.53
2019/2020	299.30			208.88	100.00
2018/2019	298.53	48.75			164.77
2017/2018	351.39				120.00
2016/2017	330.53				59.37
2015/2016	320.63				136.00
2014/2015	342.23				125.99
2013/2014	317.95		408.88		27.73
2012/2013	276.09				16.46
2011/2012	160.76				110.00
2010/2011	163.46				174.29
2009/2010	161.27				102.04
2008/2009	161.27				111.92
2007/2008	161.27		288.06		40.80

Appendix B

Data Set Links

B.1 Data set links for the case study 1

ENTSO-E links for physical flow, installed capacities, and peak demand.

entsoe.eu

transparency.entsoe.eu

ec.europa.eu

WTO Regional trade agreements.

wto.org

B.2 Data set links for the case study 2

PJM links for capacity market planning parameters and results.

pjm.com

pjm.com

Appendix C

Case Study 1: Sensitivity Tables

Table C.1: Limits on the transmission line capacity (negative direction)

Tmin		Offpeak		Mid		Peak	
		LO	UP	LO	UP	LO	UP
BG	TR	-inf	500	-inf	500	-inf	-372
BG	GR	-inf	711	-inf	800	-inf	-205
BG	RO	-inf	250	-inf	250	-inf	-500
TR	BG	-inf	-500	-inf	-500	-inf	372
TR	GR	-inf	103	-inf	210	-inf	312
TR	RO	-inf	-500	-inf	-500	-inf	59
GR	BG	-inf	-711	-800	-208	-inf	205
GR	TR	-inf	-103	-inf	-210	-inf	-312
RO	BG	-inf	-250	-inf	-250	-inf	500
RO	TR	-inf	500	-inf	500	-inf	-59

Table C.2: Limits on the transmission line capacity (positive direction)

Tmax		Offpeak		Mid		Peak	
		LO	UP	LO	UP	LO	UP
BG	TR	324	500	461	500	-372	inf
BG	GR	711	inf	800	inf	205	inf
BG	RO	250	inf	250	inf	-500	inf
TR	BG	-500	inf	-500	inf	372	inf
TR	GR	103	inf	210	inf	312	inf
TR	RO	-500	inf	-500	inf	59	inf
GR	BG	-711	inf	-800	inf	205	inf
GR	TR	-103	inf	-210	inf	-312	inf
RO	BG	-250	inf	-250	inf	286	500
RO	TR	250	500	250	500	-59	inf