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Stephen A. Roosa, Ph.D., CEM, Editor-in-Chief  
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*Editor's Desk*

## Hydrocarbon Emissions

The world's energy consumption from fossil fuels is increasing. The newly-added atmospheric hydrocarbon emissions from these sources are primarily due to emissions from combustion processes that generate heat for practical uses such as generating electricity. Carbon dioxide is released into the atmosphere by both natural sources and the combustion of carbon-containing fuels and petroleum-based distillates. These atmospheric greenhouse gas (GHG) concentrations are increasing and driving climate change on a global scale. They have the potential to negate our boldest efforts toward mitigation.

The types of energy we use and how we use our energy resources are key to our mitigation efforts. Sustainable energy sources are an important component of our solutions. Renewable energy sources can be categorized as *sustainable*, while most nonrenewable energy sources are potentially *unsustainable* and most are exhaustible. There is hope that we have time to implement climate stabilization remedies. However, the time available to implement solutions is limited.

Categories of the energy we use are divided unevenly into non-renewable sources (typically carbon-based energy sources such as coal, oil, and oil shale), and renewable sources, such as wind power, solar, geothermal, and gravitational water sources (e.g., hydroelectric, tidal and water currents). Nuclear energy is a fossil fuel which many classify as a clean energy source. Clean energy usually refers to renewables plus nuclear energy since these energy resources produce negligible greenhouse gases. Small nuclear reactors used to generate electricity are one example of a hopeful technology. However, unresolved concerns about how to permanently dispose of nuclear wastes such as spent fuel rods make nuclear energy problematic.

Most carbon-based energy forms being used as primary fuels are fossilized biomass and can theoretically be renewed, but not during the lifetime of humanity. The geophysical and biochemical processes involved require the correct conditions of temperature and pressure plus long periods of time for the renewal process to be effective. Much of the solar energy captured and stored in the Earth by fossilized hydrocarbon processes that are being extracted and consumed today date from the Paleozoic period, roughly 600 million years ago—predating mankind's existence.



Carbon-containing fuels include oil, wood, coal and natural gas. Petroleum distillates that generate carbon emissions upon combustion include gasoline, kerosene, propane and diesel fuels. Fuels sources such as those derived from waste streams (e.g., sawdust, landfill gas, animal wastes, etc.) are more difficult to classify as they are carbon-based fuels yet are rapidly renewable if the waste streams are maintained. These are typically classified as biomass fuels and considered to be renewable.

While there is movement toward greater use of renewable energy, hydrocarbon-based energy consumption is increasing. Our patterns of energy use create a host of environmental issues which remain unresolved. One of the biggest obstacles in managing environmental problems is that many are seen as international in scope rather than local. Concerted efforts by people in many diverse countries are required to ensure success. Such international cooperation over extended time frames are indeed rare. Existing institutions and national bureaucratic structures often cannot handle and were not created to deal with such problems effectively. Supra-national governmental organizations such as the UN and the EU have proved somewhat more effective. Without the institutional capacity in place necessary to handle problems on an international scale, inertia and inaction are often the result. This postpones effective resolution.

International action to prevent additional damage to our atmosphere requires international treaties. We have only one world that is presently habitable. It is wonderful and unique yet requires management. Let's work together to find common ground to find ways to move forward to reduce greenhouse gas emissions. The solutions are available in the policies we create, the programs we support and the technologies we deploy. We need to act now to ensure that our children and theirs have a promising future.

Editor-in-Chief

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# Analysis of Business Models for Electric Mobility Solutions

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## ABSTRACT

The number of electric cars has been growing rapidly, with further increases anticipated in the near future. Each country has a different share of electric vehicles (EVs) in their fleet—those with higher consumer spending, larger populations or better incentives stand out.

Electric vehicles are an emerging and developing market. Most EV owners are characterized as innovators and early adopters, many are young or middle-aged with strong financial backgrounds. Many EV owners have a garage and charge their vehicle's batteries at home during the night. Stakeholders agree that there is a need for improved public EV charging infrastructure with more services to facilitate the expansion of their use. Many studies have considered the optimal allocation of EV charging locations based on traffic data, infrastructure and financial reasons.

Another important aspect is the emerging business potential of e-mobility solutions. Our article overviews the most common e-mobility business practices in Europe in general with emphasis on those in Hungary. Furthermore, it identifies different models and clusters to identify possible joint services that can make electric mobility more attractive for business development.

## INTRODUCTION

According to the International Energy Agency, the number of electric vehicles (EVs) has been growing rapidly in the recent years, with more than 3 million cars in 2017 worldwide [1]. Every prognosis predicts increases in market size in the near future. Each country has a different share in this total, markets with greater spending power, higher populations or better incentives stand out as global leaders. In 2017, China and the United States jointly held two thirds (64%) of the world's EV fleet. Japan, Netherlands, France, Norway, the United



Kingdom (UK) and Germany also had quantifiable shares. The situation is for public charging locations. Also, in 2017 there were 318,000 slow charging (household voltages), and 112,000 fast charging (480V AC or DC up to 500V) locations available which is roughly one charging point for every six vehicles. In the case of slow charging points, the worldwide ratio between the number of cars and slow chargers is 9.75, while in the case of China and the U.S. a ratio of 9.5 and 19.5 describes the infrastructure, respectively. China has a huge advantage in fast charging infrastructure – 74% of all such stations, which is a ratio of 15 vehicles per fast charger. In the U.S. this ratio is over 110. However, car and bus charging points are not distinguished in China, a fact which could alter the ratio [1].

This is a new and emerging market. Most electric automobile owners are considered innovators and early adopters. Many are young or middle-aged with solid financial backgrounds. Belonging to this latter economic group means that most vehicle owners have a garage and typically move battery charging happens at home during the night [2]. Public chargers are more available in countries where circumstances make home charging difficult (e.g., in the Netherlands) or vehicle range anxiety is greater (e.g., in Japan) [3-4]. E-mobility market stakeholders would like to have better public charging infrastructure and services to facilitate the greater EV usage. Many past studies have discussed the optimal allocation of charging locations based on traffic data, infrastructure and financial implications [5-8]. A European Union (EU) study classifies the charging infrastructure into three separate groups, each of which serves different needs: DC chargers, fast and slow public chargers, slow home and workplace chargers [9].

Charging locations are classified as public, semi-public and private [10-11]. The most common use of direct current (DC) chargers is near the main highways. DC fast chargers offer 30-minute charging times with a range extension of 280 km to 300 km. Public chargers are often found at hotels, restaurants, shopping malls and supermarkets or other service locations where EV owners are expected to stay during the day. These types of chargers provide a 40 km to 50 km range extension when used for at least two hours. Slow charges, available in residences, garages and workplaces have less accessibility and require charge times of at least six hours.

For new infrastructure, charging stations can be included in the planning phase. Design constraints include available space, contracted electrical power and other technical restrictions. When in close proximity, charging stations are easier to connect to electric grids and less costly. A best-practice for public locations is to reserve about 10%-20% of the parking spaces for EVs.

Governments establish legal frameworks to obligate the investors that regulate the commissioning of charging stations. In Amsterdam and some other cities, residential customers can request that charging stations be provided by the municipality. The greater use EV charging at public charging locations, public transportation points or taxi stands creates revenue for providers. Charging points that more are difficult to access (e.g., apartment houses, workplaces) must be accommodated by using existing infrastructure. One solution is to create licensed single charging points and install more chargers fitted to the size of the parking areas as is done in France and in the United Kingdom (UK). From the perspective of this research, another relevant group is composed of service buildings, where the chargers could be practical for EV owners, and offer battery charging for owners who lack such infrastructure at their workplace. Service facilities include shopping malls, supermarkets, restaurants, coffee shops, main public places, sport centers, office buildings and public buildings.

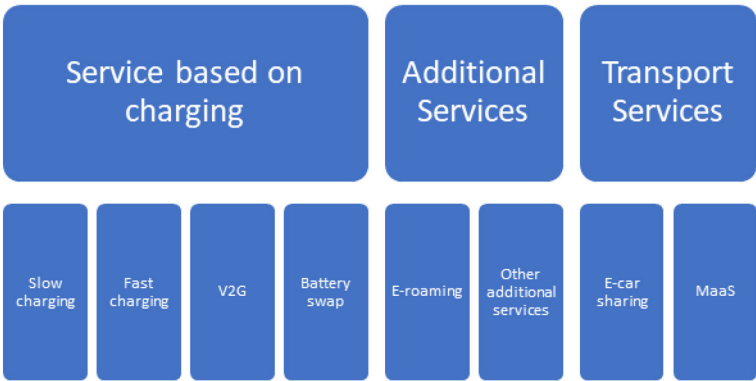
The variations among user groups include differences in vehicle types, charging power requirements, number of users, user profiles, enabling legislation and forms of regulation. To explore these variables further we next consider international and national examples of e-mobility business models.

## OVERVIEW OF EXISTING E-MOBILITY BUSINESS MODELS

The modern electromobility industry is at an early stage of development. Participants in central and western Europe focus on technology, standardization and legal conditions. For the e-mobility market to function smoothly, an inclusive business environment is needed that supports sustainable business models.

Classified business models that may exist in 2020 have been researched based on interviews with experts [12]. In one study, experts evaluated the relevance of the given concepts on a three-value scale (with 3 ranked the highest, and 1 the lowest) [12]. Figure 1 categorizes business models as services based on charging, additional services and transport services. After studying several papers on the subject, we concur that these models cover the range of economically sustainable services anticipated in the near future [12-20].

Next, we provide a structured overview of existing business models in the e-mobility market based on existing studies, analyze their potential and draw conclusions about how to apply these models. The following classification of business possibilities were defined by Laurischkat et al. and other sources [13].



**Figure 1. Categorization of business models in electric mobility.**

**Electric Vehicle Sharing**

The electric car-sharing business model includes a vehicle fleet that is available to a limited user group in a specific business region. An important advantage of car-sharing is the value created both for customers and sharing service providers. The high cost of vehicles, lack of parking spaces in urban areas, changing attitudes toward vehicle ownership and the decreasing importance of vehicles as status symbols are major drivers of the EV car-sharing model. Normally, vehicle use times for car-sharing programs are shorter than for car rentals.

Autolib is an early French example of a car sharing strategy that reduces costs and offers a positive value proposition for the user. The primary benefit of the service is the information and communication technology (ICT) functionality. The Bolloré conglomerate initiated the distribution of its own battery technology in Paris, France offering opportunities to benefit from infrastructure, software and energy management.

Unfortunately, after enlisting 150,000 subscribers, the business viability of the service remains unproven. For the period 2018-2023, a budget deficit of €294 million was predicted. The Paris City Council decided to terminate its contract with the company. Based on this experience, it is clearly important to thoroughly examine each project’s feasibility, revenue opportunities, level of investment costs, and perform a life cycle cost analysis during each design and development phase [14].

Budapest, Hungary, has another example of a company using the car sharing business model. GreenGo which has 800 electric vehicles available during peak periods combines services with public transportation, some mobile ap-

plications, and provides special offers at important transportation points (city center, main rail stations, etc.) [15].

### **Intermodal Transportation Services**

Intermodal transport refers to customers using different transportation modes and services (both private and public). An intermodal service provider collects the various offers from market suppliers and provides a common platform for route planning and central billing.

The European Commission (EC) investigated the potential of personal multimodal mobility solutions within the EU and published the results in 2013 [16]. In addition to developing new business models, the EC created the role of mobility integrator to drive mobility solutions; they are needed to override traditional market competition. The EC found that many solutions offer an ICT-based approach, such as a personal mobile transport assistant.

Klug's research mentions several pilot projects [16]. One of these, a pilot called SMILE that was implemented in Austrian cities (such as Vienna and Graz), has created an integrated transportation platform with personal assistant services. Public transportation companies were the primary drivers this innovation. SMILE evolved from the eMORAIL project, which supported the use of EVs between different public transportation stops, giving travelers the fastest possible transfer.

A pilot project called OPTIMOD'LYON was launched in Lyon, France [16]. Within this framework, a multimodal ICT platform was created integrating data from various sources for different e-mobility and transportation services (e.g., car sharing). The purpose of integration was to reduce congestion and develop mobility information services for citizens and suppliers in the city. Services connecting to this platform included a forecasting tool, a multimodal global positioning system (GPS) with real-time and predictive information plus a freight navigator.

The 2020 vision of the National Electric Mobility Platform in Germany is designed to meet specific transport and delivery needs with the highest possible availability and reliability [16]. The roadmap consists of four main sections, one of which includes urban planning and intermodality, and focuses on establishing and developing mixed transport services for major cities including personal, public or car-sharing services. To achieve these goals, it is necessary to clarify legal issues and obtain support from businesses who can help develop innovative ideas and support their long-term viability.

Weiller and Neely examined two cases to define mobility as a service [17]. One was the ServCo 1 company, which emerged from a large Norwegian

Table 1. Results of expert interviews on e-mobility business models based on [12].

<i>Name of business model</i>	<i>Description of business model</i>	<i>Rank</i>	<i>Answer</i>	<i>Type</i>
Invoicing through a domestic energy bill	Charging fees are transferred to a domestic electricity bill, while electricity and e-mobility fees are paid at the same time.	1	2.82	Additional services
Electric Vehicle – Green Energy Integrated Offer	Unified offer for green electricity contracts and electric vehicles.	2	2.75	Additional services
Leasing of electric cars	Rental of electric cars.	3	2.67	Mobility solutions
Parking and charging	The car is charged while parking.	4	2.58	Service based on charging
On-demand mobility	On-demand mobility (or car sharing) ensures the proper use of any car in a specific fleet. Billing can be based on usage time or kilometer.	4	2.58	Mobility solutions
Energy production infrastructure	The infrastructure is operated by local energy producers.	6	2.55	Service based on charging
V2G electricity trading	The battery is used as a transactional element for trading with power.			Service based on charging
Finding free charging stations online	The battery owner can benefit from arbitrage by buying at a low price and then selling electricity at a high price. An Internet application that helps you find free charging stations in a direct geographic environment.	7	2.5	Additional services
Intermodal transport	Integrated offer of different means of transport: e.g. electric vehicles	7	2.5	Mobility solutions
		9	2.42	

for traveling within the city or trains at a greater distance.				
Rental of batteries	Rent batteries while the vehicle itself is purchased.	9	2.42	Service based on charging
Fast Charging	Fast charging allows for a much shorter charging time than the conventional method.	9	2.42	Service based on charging
Infrastructure provided by new players	The infrastructure is operated by new e-mobility service providers. The clearing house is responsible for the involvement of the infrastructure provider and the buyer in the billing process, which also includes a roaming infrastructure, but provides services related to the charging process.	12	2.36	Service based on charging Additional services
Clearing house platform	This business model focuses on selling smart home systems that are integrated with electric vehicles.	13	2.33	Additional services
Selling smart home systems	The car application shows the electricity consumed during the given time frame.	14	2	Additional services
Show power consumption in cars	The service provider does not operate the infrastructure but provides services related to the charging process.	14	2	Service based on charging Additional services
Service Infrastructure	The aggregator is a player that can use the elastic load of electric vehicles to design and sell new products	14	2	Additional services
Aggregator	Car services are services that can be used during charging. For example, it may be music or other media services.	14	2	Additional services
Car services	Inductive charging allows you to charge the battery without a wired connection between the charging station and the battery.	14	2	Service based on charging
Wireless charging		14	2	



company in 2007 and started with a traditional model allowing the rental of electric vehicles. This case was one of the earliest initiatives to sell e-mobility services. This business model markets EV rentals as an innovative eco-friendly alternative to vehicle with internal combustion engines. Focusing on the customers, the company provides integrated services for EVs including repair and maintenance, online booking and recharge management. Customers pay a fixed monthly subscription and usage fee rather than purchasing a vehicle and bearing the risks associated with vehicle ownership. Battery charging costs are invoiced and paid directly by the subscribers. The company partners with vehicle manufacturers, including Mitsubishi and Nissan, to purchase EVs. The business model separates problems related to vehicle manufacturing, electricity supply and charging infrastructure (corporate customers are responsible for their own charging stations).

An example of mobility-as-a-service is providing urban transport by electric vehicles as commissioned by the French government [17]. User behavior is important to this model's success. It features a public vehicle sharing service operated in a partnership between an industrial conglomerate and a local government. This business model reduces the investment cost in EVs by using its own compatible battery technologies and including electricity costs in the recharging fees. User ownership of the EV is optional. Like the ServCo 1, this business model is limited to urban use and is not applicable for users who need EVs for long distance journeys.

### **Vehicle-to-Grid Solutions**

Surprisingly, privately owned vehicles are in use only 4% of the time and are otherwise idle [18]. In the vehicle-to-grid (V2G) business model, the battery storage capacities of the idle electric vehicles can be used. When idle and grid-connected, vehicle owners can earn income while their EVs are connected to the grid. This happens when network operators purchase battery storage capacity to control load peak. Using renewable energy generation resources, such as solar, electricity is stored when excess is available. Aggregators are needed for the success of this model. This V2G developer delivers the aggregated excess capacity of the EVs to the network operator, thereby offering a MW-scale aggregation. In this way, connecting the EV to the power grid is mutually beneficial for the vehicle owner, the aggregator and the network operator.

Numerous attempts have been made to implement V2G programs. In Colorado in 2013, a military base post office used EV battery storage as a backup electricity source [19]. In 2014, at the Southwest Research Institute in Texas, the first autonomous frequency control project was implemented [20]. There was

a similar effort on Bornholm Island in Denmark: in the “EDISON” project, EV batteries were recharged with electricity from local wind power plants [21]. V2G is still in its early stages of application. In Japan, the Mitsubishi Outlander has a V2G option. In Europe only the Nissan Leaf and Nissan e-NV200 were capable of V2G functionality, although it would be better to call this functionality vehicle-to-home (V2H). Nissan batteries can be connected to the grid for home charging and used as for electricity storage when recharged during periods of low electric demand and discharged during peak periods, network failures or power outages. Honda also has experimental V2H solutions.

### Battery Swapping

In this business model, consumers purchase the electric vehicle but lease the batteries. They can use a network of battery swapping stations for a monthly subscription fee. At these stations, the discharged battery is replaced with a fully charged one in a few minutes. The service fees are calculated based on the projected distance traveled by the EV [22]. According to Weiller, and Neely, for EV battery exchanges to succeed, the ownership of the battery and the vehicle must be separated and the users’ subscription for the recharging service must be resolved [17].

The advantages of the battery swapping as a business model is that it reduces the vehicle time at the station may ideal for consumers who travel long distances. Customers obtain usable batteries with a lower capital investment. Since recharging the battery is included in monthly subscription fees, customers are less concerned with electricity prices.

A practical example was Better Place venture-backed international company that developed and sold battery-charging and battery-switching services for Evs in California. Founded in 2007, their model bound partners and consumers to a platform company. This can lead to a monopoly situation, which may ultimately impact technological innovation. Better Place had a vision of its market potential, appropriate market knowledge, and adequate venture capital. Despite a nearly \$1 billion investment, the company was unable to convince the rest of the industry, especially car manufacturers that its model was workable. Ultimately, the company was not able to play a central role in the e-mobility market in California due to its limited business model and filed for bankruptcy in 2013 [23-24]. Another example of this solution is the Tesla Battery Swap pilot. With the Tesla Model S, it was proved that vehicle batteries be can quickly and safely replaced rather than recharging them when the appropriate infrastructure is available. Despite successful testing of the battery exchange business model it has not been adopted commercially [23].

### **Fast Charging**

The electric vehicle fast-charging business model is one solution for traveling long distances with EVs when long recharge times are inconvenient. This business model focuses on the charging infrastructure and not on the financial constraints of the consumer. Owners bear the risk of buying an EV vehicle, while the responsibilities for development and market risks are shared among the allied companies. The business advantage of the fast-charging model is that since it uses an intelligent charging infrastructure, it can adapt to the inputs determined by different market participants. The service can be compatible with other business models including charging networks and user mobility services. Fast charge imposes a heavy burden on managing the electrical grid because of the short-term peak demand it creates. To address these risks, fast charging businesses must optimize EV charging and implement load management with intelligent electrical network technologies.

### **E-roaming**

For consumers using e-mobility systems two considerations are how long a distance they can travel with a full charge and the accessibility of recharging locations and infrastructure. Being unable to travel very far with a single charge is a disadvantage. The longer the battery lasts on a single charge, the higher the value to the consumer. In the e-roaming business model, infrastructure providers are connected to a roaming platform through which consumers have unified access to the charging infrastructure. Laurischkat et al. suggest that this e-roaming is one of the least-researched business models; car-sharing, for example, is mentioned nearly five times as often in literature [13].

Generally, e-roaming is a multilateral platform that includes two core value propositions: 1) the increased utilization by service stations of service providers; and 2) consumers receive service-independent, cross-border tariffs.

Noyen et al. set five functional key requirements for e-roaming platforms [25]:

- A platform independent of the business model is needed. In the case of mobile phone roaming, foreign service provider fees must be clarified under the terms of the native service provider.
- Interoperability between different information technology (IT) systems needs to be ensured, as the platform should work with all systems and smaller, personalized applications. In addition, there are interfaces between systems used in different industries.

- The consistency and correctness of the data used on the platform must be ensured because it is working with aggregated data from different sources.
- The platform needs to be reliable.
- Data security is crucial as large amounts of sensitive customer data are used by market participants in the mobility platform.

The Hubject platform is capable of storing, retrieving and providing e-mobility transaction data based on the above functional requirements [25]. The relationship between EV users and their service providers is similar to those between the telecommunication service providers and their customers. The difference is that EV users are more dependent on the contracts between the service providers as they cannot reduce or stop using roaming. E-mobility service providers generally want to provide the largest possible re-charging infrastructure to reduce customer concerns about access. However, they compete with the local enterprises. Financial incentives for e-mobility service providers may be required.

Such an e-roaming service was implemented by Hubject, which enables data and transaction information to be communicated through its B2B platform between electricity providers, car manufacturers and infrastructure managers. The communication protocol used is Open InterCharge Protocol (OICP). Hubject's goal was to provide independent access to the public and semi-public charging infrastructure, thereby helping to connect European e-mobility markets. There are other such companies that provide eRoaming, such as: NeMo (<https://nemo-emobility.eu>); has-to-be eMobility, eMSP.OPERATION (<https://has-to-be.com/en/services-emobility/emsp-operation>); however, the OICP is a leading protocol for e-roaming services.

### **Other Related Services**

An example of a connected (or related) service is a restaurant or hotel that provides opportunities to purchase and consume food along with other services. The connected service approach is based on idea that it is beneficial to offer consumers related services while their EVs are recharging. The connected service may be optimization or efficiency (e.g., fast charging with electric vehicle).

Heindl et al. believed that an integrated approach is needed to develop e-mobility service models [26]. They concluded that in the e-mobility market, customers need to be addressed by an integrated approach that offers infrastructure services, platform services and software, including energy, traffic, and

information technology management. The main challenge is to integrate all systems and services within the affected areas by defining a common standardized information model.

In 2010, Briggs identified six key stakeholder groups in the e-mobility market for corporate profiles: battery, vehicle, infrastructure providers, power suppliers, system integrator and billing companies [27]. These are all integral parts of the e-mobility service value chain. Cooperation among companies is important for business success as each e-mobility marketer typically supplies only a part of the entire value chain. We believe that successful business models might use a variety of methods. Segmentation and filtering of the customer's procurement circle is relevant (e.g., targeting specific consumer groups or business users). Other dimensions include the geographic locations, the types of technologies (unique or multi-technology service) and the roles of service providers (e.g., car sharing or direct manufacturer sales).

By 2010, a large number of e-mobility pilot projects and development proposals were already implemented in the U.S., Japan, England and Germany. The expansion of recharging infrastructure for EVs at that time also had initiatives in China as developing e-mobility business models became a global issue.

For China, Li et al. analyzed and compared the advantages and disadvantages of known e-mobility business models [28]. The purpose of their study was to learn how to maximize the overall benefits for all stakeholders in China's market value chain. The aspects they collected can be interpreted not only for China but also for other underdeveloped or developing countries. The indicators used in their analysis were: the scale of the project, the basic competitiveness of the industry in the analyzed country, the social benefits of solutions, and the levels of risk [28]. They divided e-mobility services into two main categories: those that required charging and others that needed replacement batteries. Considering mainly user satisfaction, they distinguished the users of private and commercial vehicles. They concluded that the most appropriate strategic choices for China were battery replacement as the main service, charging as an additional service, centralized recharging and a unified distribution system.

## CONCLUSIONS

It is important to emphasize that in most cases e-mobility business models include connected services, i.e., a combination of several existing services. These can be services within the e-mobility market provided as a single package (such as a combination of vehicle fast-charging technology and charging

infrastructure), or mixed-type services (e.g., food shopping facilities at charging stations).

In addition to the models reviewed in this article, there is a huge potential market for electric vehicles and related services. For example, automobile manufacturers such as Nissan and Mercedes have developed residential energy storage options using automobile batteries for ancillary services (second-hand recycling). There are also attempts to integrate small-scale household power plants to support the implementation of residential charging systems. Some of the discussed methods exist today as pilot programs, but others are only in the design phase. There are large-scale, unsuccessful attempts to provide services (see Autolib), which is why it is necessary to carefully define the proposed services in the planning stage and evaluate their cost implications. Further research is needed in the field of e-mobility, as the market is in the initial phase of a Gartner Hype Cycle, a phase of growing enthusiasm and rising expectations for the technology, and further innovative solutions can be expected in the future [29].

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# Engineering Policies for the Climate Change Resilient Built Environment

*Ali Syed*

## ABSTRACT

Successful implementation of climate resilient pathways for sustainable development requires an understanding of energy, linkages with greenhouse gas (GHG) mitigation and adaptation considerations, technical innovations and behavioral change. This article provides a knowledge exchange about the energy and GHG spectrums of the built environment from academic, scientific and practitioner perspectives. The goal of this article is to present useful solutions concerning green engineering design policies to reverse increasing fossil fuel energy use and GHG emissions in the built environment. The article also discusses practical tips and limitations of certain renewable energy technologies. It provides capacity-building tools for policy makers, communities, individuals, practitioners, architects and designers concerning the development of sustainable and climate resilient cities.

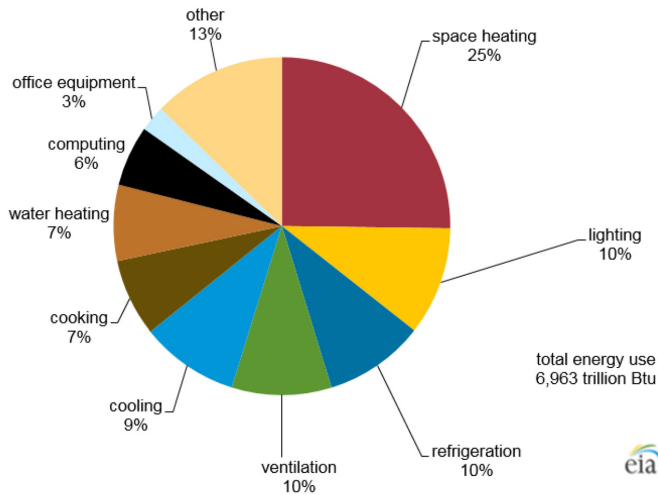
## INTRODUCTION

According to United Nations (UN) Habitat, the world's cities contribute 70% of global greenhouse gas emissions while occupying only 2% of the world's land surface [1]. Other UN estimates show that by 2050 two-thirds of the world's population is projected to be living in urban areas [2].

Such immense urbanization requires planning and design strategies to mitigate resource consumption, reduce energy use and lower the carbon footprints of buildings to create less carbon-intensive cities. This article aims to expand practice-based knowledge to identify the systematic linkages and synergies between the urban built environment and climate change by exploring energy use and GHG emissions. It elaborates on how building science can guide cities toward reducing their energy and GHG footprints through adaptation of green building policies that support mitigation of GHGs. These changes apply to architectural design, mechanical and electrical engineering and renewable energy (RE) system applications.

## OVERVIEW OF SECTORIAL ENERGY DATABASE

Figure 1 presents an energy end-use budget for a typical building in the United States [3]. It shows that approximately 51% of energy use is related directly to the mechanical systems, 26% to electrical systems and 23% to other miscellaneous systems.



**Figure 1. Typical building energy end-uses [3].**

## POLICIES FOR CLIMATE CHANGE RESILIENCE

The following sections explore practical design policy opportunities to implement energy saving measures and GHG mitigation strategies for urban buildings to reduce the impacts of climate change. They present an overview of prominent energy policies and design strategies that can make urban infrastructure more resilient.

### **Green Building Sustainability Codes and Standards**

Most of the world's nations have developed and implemented some form of building design and sustainability codes. The imperative first step towards climate change mitigation is to incorporate primary sustainability considerations in architectural, mechanical, plumbing and electrical design requirements, especially those for jurisdictional codes and sustainability standards. There are numerous green building standards included in many national or municipal

policies; it is crucial to mandate green building design, construction and facility operation and enforce compliance with the most stringent applicable codes/standards. Examples of widely-adopted design guides and standards published by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) are noted below:

- ASHRAE 90.1—Energy Standard for Buildings Except Low-Rise Residential Building [4]
- ASHRAE 189.1—Standard for the Design of High-Performance Green Buildings [5]
- ASHRAE 62.1—Ventilation for Acceptable Indoor Air Quality [6]

These standards provide a set of design requirements green buildings. It is important to comply with all applicable sustainability standards and codes.

#### **Green Fuels and Utility Rates**

It is important to adopt policies that incentivize the use of fuels with the lowest carbon footprint. Renewable energy resources such as the many types of biofuels are examples of green fuels. Several leading organizations provide assessment and design tools for designers and developers to estimate GHG and carbon footprints. Examples include Natural Resources Canada and the United States Environmental Protection Agency [7,8]. Promoting the use of these design tools and installing energy-efficient appliances, equipment and technologies with lower GHG impacts is paramount.

In addition, it is important to use the utility rate structures that provide incentives to maximize operating cost savings. Savings from reduced operating costs achieved by reducing fossil fuel use helps improve the financial viability and economic viability of energy conservation measures [9].

#### **Sustainability Policies for Architectural Design**

The following basic examples of architectural design practices have been proved to achieve significant energy use reductions and also reduce the carbon footprints of buildings [5,6,10].

- Minimum requirements for the building envelope shall be based on local climate conditions and other regional requirements
- Use effective R-values rather than nominal ones when designing the building shell
- Reduce thermal bridging to prevent building heating and cooling losses

- Base designs on the overall window assembly U-values not on the center of glass U-values
- Install appropriate moisture barriers

Figure 2 shows climate zones across the U.S. as indicated in ASHRAE 90.1 (2016) [4]. This guideline offers minimum building envelope insulation requirements for a variety of climates. As a policy, it is important to mandate applicable codes and standards that reflect relevant building envelope insulation requirements suited to a specific region.

The International Energy Conservation Code, developed by the International Code Council, is an example of a standard that has been widely adopted by cities and regional governments throughout the world. It establishes baselines for energy efficiency by setting specific climate-adjusted performance standards for the building envelope.

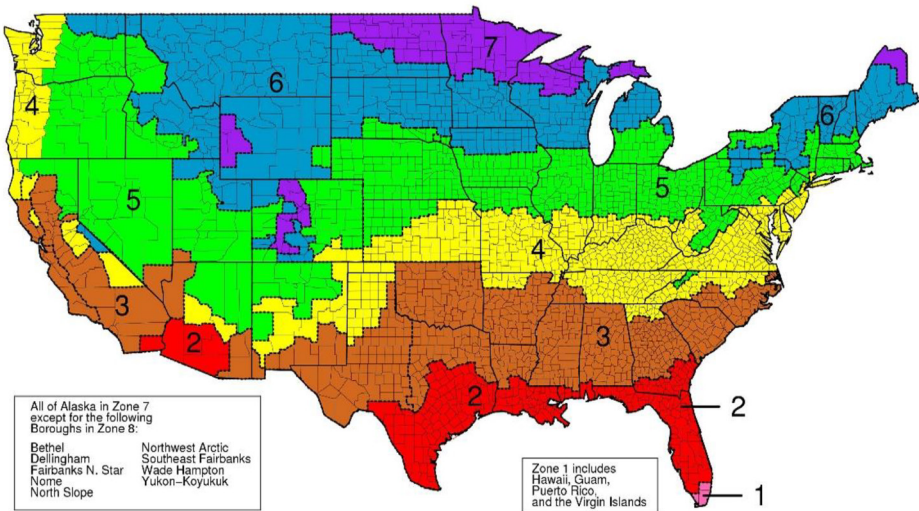


Figure 2. ASHRAE climate zones [4].

### Sustainability Policies for Mechanical Design

The energy used by mechanical systems represents 51% of annual building energy use in the U.S. [11]. Hence, it is important to mandate high efficiency and energy conserving mechanical systems in all national or municipal building codes. Many features related to green mechanical heating, ventilation and air-conditioning (HVAC) design when incorporated as policies provide substantial energy savings and help reduce the carbon emission footprints of buildings.



Examples include the following [4,5].

- Avoid gross oversizing of motors, pumps, boilers and chillers as it lowers performance efficiencies and increases operating costs
- Avoid over ventilation as it results in exponential increase in operating costs and waste of energy
- For hospitals and research laboratories with high ventilation requirements adopt green laboratory ventilation standards (e.g., ANSI Z9.5, 2012)
- Lower energy loss from hydronic pipes and ventilation ducts by insulation
- For cooling applications mandate the use of waterside economizers
- Use condensing boilers for building heating
- Mandate variable speed chillers over single speed chillers
- Mandate variable speed cooling tower fans
- Use magnetic bearing chillers
- Water treatment and cooling tower basin sediment removal should be mandated

#### **Sustainability Policies for Electrical and Lighting Design**

The following lighting and electrical design features when incorporated as policies achieve significant energy reductions and thus reduce the carbon footprints of buildings [4,5,12].

- Lower lighting power density ( $\text{W}/\text{ft}^2$ ) by electronic ballasts, light emitting diode (LED) lamps etc.
- Effective lighting controls and optimized schedules
- Smart car block heaters
- Mandate EnergyStar rated appliances and optimized their schedules
- Use premium efficiency motors for fans and pumps
- Use variable frequency drives, where applicable
- Contract time of use electricity rates and mandate demand management
- Mandate power factor correction for all electrical appliances

#### **Sustainability Policies for HVAC Controls**

The following HVAC control strategies achieve significant energy and thus reduce the carbon footprints of buildings [4,5,9].

- Avoid simultaneous heating and cooling by using best design practices
- Mandate demand-controlled ventilation for variable occupancy

- Perform morning warm-up/cool down with outside air vents closed
- Mandate optimized HVAC start-up to reduce energy wastage
- Optimize temperature set-points and incorporate night set-back
- Mandate free economizer cooling, where applicable

### **Sustainability Policies for Plumbing Systems**

The following plumbing design methodologies as design policies have shown to achieve significant energy reductions and thus reduction of carbon footprint in the built environment [9,13].

- Mandate condensing domestic hot water boilers
- Require continuous detection and fixing of water leaks
- Mandating low flow faucets and low flow showerheads
- Mandating low flow urinals/water closets and low flow aerators
- Incorporating plumbing faucet controls (e.g. electronic, hands free, push spring)
- Using water efficient clothes washers
- Reuse wastewater for water preheating

### **Sustainability Policies for Renewable Energy**

Use of onsite renewable energy systems to offset building energy cost is a prevalent strategy [13]. For any climate change resilient urban development policy, it is important to assess the potential of non-polluting and RE systems including solar, wind, geothermal, low-impact hydro, biomass and bio-gas strategies. With any RE strategy, it should be mandated to take advantage of net metering opportunities in partnership with the local utilities [14]. As utilities adapt to increasing levels of intermittent energy resources on their systems, the benefits and avoided costs that local governments and utilities use to evaluate cost-effectiveness of their policies must be considered [14]. Detailed discussion of RE systems is beyond the scope of this article. However, there are several national and municipal tools provided by many nations across the globe for the RE potential for the project site [see reference 11].

## **CONCLUSIONS**

Based on the world's projected population growth and forecasts of urbanization, there are pressing needs to address climatic impacts. Urban planning and design strategies offer opportunities to mitigate consumption of fossil fuel

resources and help reduce the carbon footprints of buildings. This article is a primer for research on sustainable buildings and the resilience of urban cityscapes.

The goal of this article was to present useful solutions concerning green engineering design policies to reverse mounting energy use and GHG emissions in the built environment. It offered knowledge about the energy and GHG spectrums of the built environment and presented useful solutions to advance green engineering and design policies to reverse increasing energy use and GHG emissions. It presented a holistic approach toward optimizing design parameters and integrating energy conservation measures and renewable energy technologies in policies that promote greener urban environments. Climate change resilient policy-making for the urban built environment needs to explore the systematic linkages and synergies between the engineering design policies, environment and climate change, utility infrastructure and GHG emissions. This article elaborated on research-based and best practice policy suggestions for the architectural, mechanical, electrical, lighting, plumbing and HVAC design of buildings. This policy-based knowledge can be used as a basis of developing guidelines for cities through a transformative mitigation-adaptation of green policies in their engineering of the architectural, mechanical, electrical and RE system designs.

To lower carbon emission impacts, it is crucial to incentivize fuels with the lowest GHG footprints, adopt stringent architectural design parameters to suit each climatic zone, and enforce sustainability concepts in architectural, mechanical and electrical designs. In addition, integrating intelligent control systems, instituting water and energy conserving plumbing policies and promoting RE systems are paramount for mitigating GHG-influenced climate change. Policy makers should promote multidisciplinary integrated approaches to implement energy efficiency and optimize the synergistic links of sustainability policies. If research-based design policies and best practices are adopted then pathways toward futureproofing building systems and climate change resilience can be achieved.

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# Wind Power Characteristics and Feasibility for Electrical Energy Generation

*Mohammed Bou-Rabee, Zuhairi Baharudin,  
Shaharin Sulaiman and Muhammad Naz*

## ABSTRACT

An investigation was conducted on the qualities of select wind-related variables to consider utilizing energy from wind to generate electrical power. The purpose of our study was to use predictive models to forecast wind speeds at specific locations in Kuwait. A four variable dataset was analyzed using variables gathered from three locations in Kuwait, namely Abdaly, Kuwait International Airport (KIA) and Al-Wafar. Before calculating the anticipated likelihood for the production of electricity in the subsequent phase, the available data's dynamics were analyzed. Averaged over one year, wind speeds for these areas ranged between 3 m/s to 6 m/s. The Weibull distribution was used to obtain the power density of wind at a 70 m height above ground level (AGL) which varied from 70 W/m<sup>2</sup> to 179 W/m<sup>2</sup>.

For the wind data at heights of 2 m to 70 m, the power law pertaining to extraction at standard height was used. An observation was made that at a 70 m height AGL, the power density of the winds ranged from 161 W/m<sup>2</sup> to 294 W/m<sup>2</sup> with a mean of 81% the peak power density. It was also observed that the wind strength together with electricity demand were highest throughout the sunny season. Wind power density for a prior month was developed using an artificial neural network plus a hybrid forecast design on a genetic algorithm. Reasonably high prediction accuracy was demonstrated by the prediction model's results.

## INTRODUCTION

Fossil fuel sources are non-renewable forms of energy. A primary cause of oil and gas reserve depletion is the increasing demand for energy brought about by industrialization [1-2]. Today an array of renewable energy (RE) sources are utilized to generate electricity. These include wind power, biomass, solar

photovoltaic (PV) and thermal systems, geothermal energy, tidal energy and others [2]. From these, solar PV and wind energy are among the most viable options for the production of electrical power in Kuwait. Researchers have focused their attention on wind energy because of its availability throughout the year and its low costs. For these reasons, wind is a prime source of RE in many developed nations and developing nations such as Kuwait, an important oil producing country. For electrical power generation, the oil machinery industry and new factories use 25% of the oil produced domestically. The extensive fossil fuel infrastructure and related industries have increased environmental and health concerns for residents in the country, increasing the urgency to reduce fossil fuel consumption to manage air pollution.

Wind speed at a particular height, its direction and variability are used in determining a site's wind energy potential [1-2]. Researchers use numerous methods to analyze these wind's characteristics. Weibull and Rayleigh methodologies are typically used by applying analysis programs such as like WAsP and Wind Atlas [1]. Multiple time periods (e.g., monthly, quarterly and annually) are assessed for wind speed data's diagnostic evaluation.

### **Global Standing of Wind Energy**

A report by the World Wind Energy Association states that the total wind volume recovery worldwide was more than 356 GW in 2015 [3]. There was 14 GW of new wind power development in 2013 with an additional 17.6 GW in the first half of 2014 [3]. This demonstrates remarkable growth in the utilization of wind power. According to the report, Europe has overtaken Asia as the leading wind region. Brazil has become the world's third largest wind turbine market.

Numerous research studies to assess the potential of wind power development were carried out in the U.S. and European countries. Figure 1 depicts the world's installed RE capacity from 2006 to 2016. Figure 2 depicts the global electrical capacity of wind power from 2005 to 2015. Figure 3 illustrates the leading countries, comparing installed electrical capacity over the previous five years [4]. A maximum installed capacity of 145 GW makes China the world's leader with the U.S. second. A total of 15.9 GW was added in the U.S. in 2014 increasing its wind generation capacity to 73.9 GW. As revealed in Figure 3, India, Spain, and Germany are also among the top-rated wind power countries [1].

In 2015, wind electrical generation capacity of 131 GW had been realized by European onshore development with another 11 GW offshore, totaling 142 GW. The European nations have 38.0 GW of fixed wind energy capacity. Numerous wind energy projects have also been developed in India, Turkey, Japan, South Korea and Pakistan.



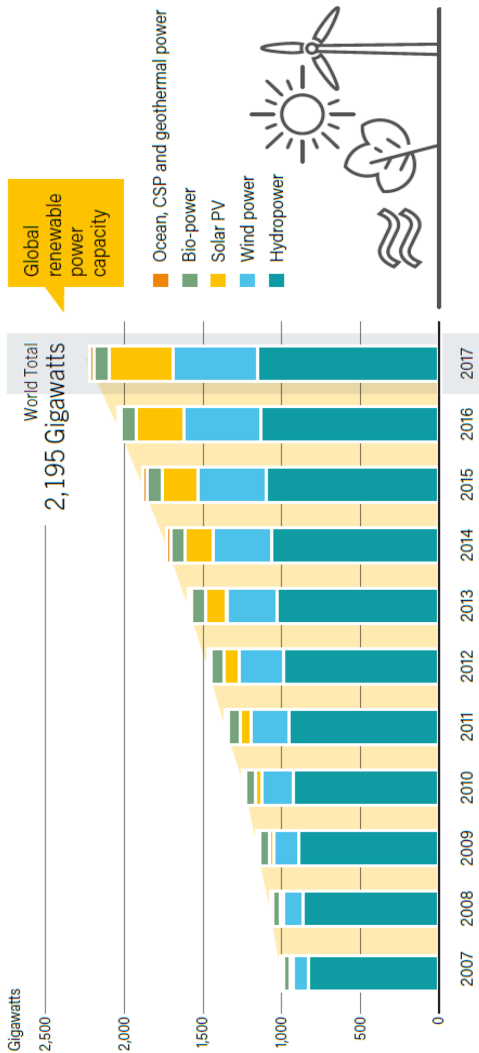


Figure 1. Statistics on the global renewable power capacity from 2007 to 2017.  
Source: <http://tracker.newenergyupdate.com/tracker/projects>.

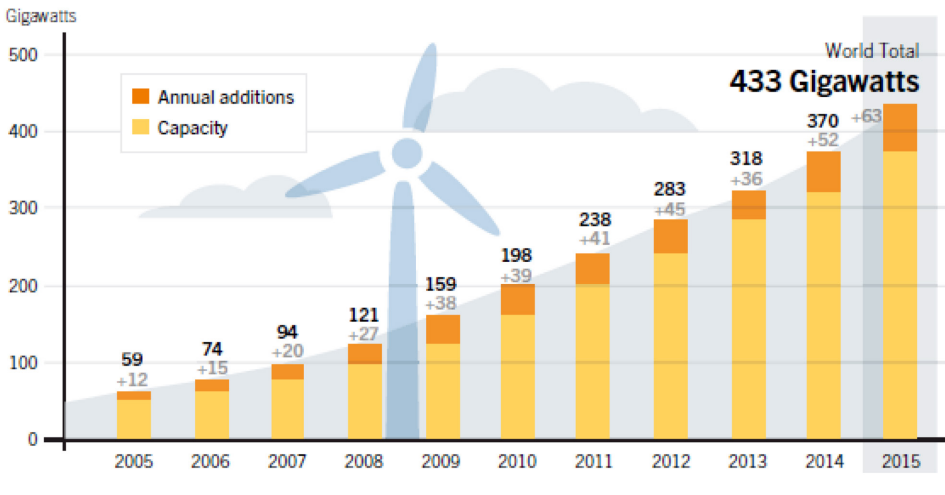


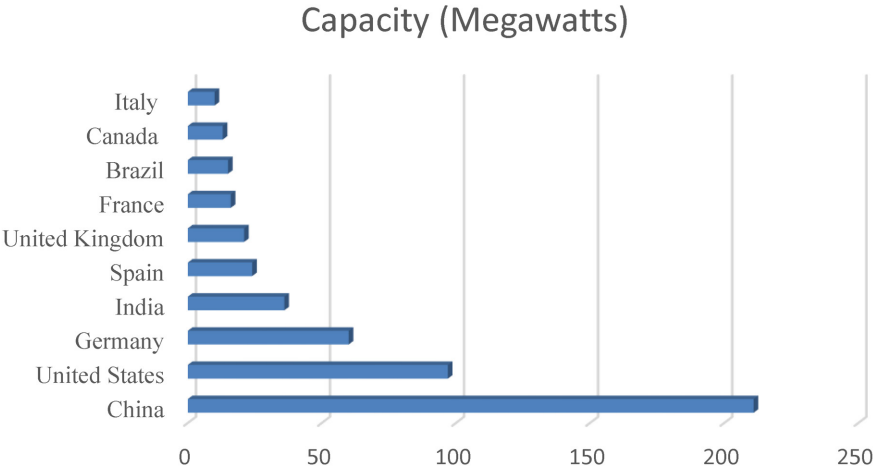
Figure 2. Global capacity of wind power from 2005 to 2015.

Table 1. The largest wind markets in Africa.

	Countries	Operational (MW)	Under construction (MW)
1	South Africa	1,170	840
2	Morocco	870	50
3	Egypt	750	0
4	Ethiopia	320	0
5	Kenya	14	320
	Total	3,124	1,200

The five largest African wind markets are shown in Table 1. There are 3.1 GW in operation with another 1.2 GW under construction. South Africa leads with a total of 1,170 MW followed by Morocco, Egypt, Ethiopia then Kenya, with a total of 870 MW, 750 MW, 320 MW and 14 MW respectively [1].

Energy requirements have increased due to population increases in the developing nations. Compared to many renewable energy sources, the cost of generating electrical energy using fossils is extremely high. Because of this, developing countries might consider shifting to using RE resources.



**Figure 3. Capacity of installed wind energy development in the world’s top 10 nations [4].**

According to an evaluation by Mostafaeipour et al. on wind’s energy generation potential for Binalood, Iran, it was determined that the area investigated was able to supply power for a sizeable grid-connected system [5]. An inquiry into the wind energy characteristics of 68 locations in Iran was conducted by Alamdari et al. [6]. In their study, they analyzed how wind speed varied annually, seasonally and diurnally. To assess its investment potential an economic and technical evaluation is required [7-9]. Past literature offers a considerable number of examples of economic evaluations about the potential of wind energy resources in various regions in the world [10-15]. Financial assessments of a number of potential locations in Turkey were completed by Vardar and Çetin and Celik [15,16]. A cost analysis of 20 places in Saudi Arabia was provided by Rehman et al. [17]. Nouni et al. presented a technological and economic evaluation of minor wind power generators [18]. Nonetheless, a most of the previous research is not empirical.

METHODOLOGY

Our study uses wind frequency, direction, and speed to exam the energy from wind at three separate locations in Kuwait. The wind energy potential was based on a thorough statistical evaluation of wind characteristics. Features included the mean wind speed and its frequency distribution. A tool for the

exact perspective of wind energy estimations at elevated heights is the Weibull distribution, which matches the frequency regarding wind together with its time series [19-20]. The vertical wind velocity deviation,  $i$ , is key to the analysis of wind energy potential. For this, wind parameters were extrapolated for the 10 m to 70 m peaks based on the power law. The variables  $c$  and  $k$  as Weibulls' parameters were determined and applied to estimate the wind power density (WPD) for each Weibull distribution function [21-22].

An exhaustive analysis for each year's four seasons was performed to examine how the wind power potential of the three locations were affected by seasonal changes. One day ahead models were developed and used for forecasting the artificial neural network (ANN). This, together with a hybrid model which joins ANN with an evolutionary computational technique genetic algorithm (GA) to forecast the wind's short-term power density. The model entails three input variables and one output energy variable, namely *relative humidity*, *wind speed*, *generation hours* and *wind farms* respectively. The modeling procedure was performed using MATLAB simulation software. The method used to assess the model's accuracy was to compare the simulated results with the measures of the actual values within the wind holdings. Using the modeled prediction results and data, the prospects for wind power at each site were evaluated to determine the best location.

### Quantitative Data Analysis

The three locations in Kuwait used to extract the analyzed dataset were Kia, Al-Wafar and Abdaly. Daily wind samples were used to develop the metrological variables that comprised the dataset. *Wind trajectory*, *speed*, and *maximum wind speed* were the variables considered. A quantitative and statistical analysis of the data was conducted to consider the data's dynamics. This research provided the mean values, medians, standard deviations, maximum values and means. The number of standard deviations, which were two, three standard deviations as well as three standard deviation outliers. However, they are unnecessary for training data to efficiently estimate wind potential.

### Parametric Analysis and Calculations

The density of the power of wind at a given location relies on the wind power potential as opposed to the direction of the wind. The following procedure was followed to perform the parametric analysis. First, the annual wind speed averages for each site at a height of 10 m AGL were compiled. The Weibull distribution function was deemed suitable to meet the probability distribution of computed wind speeds at a particular location during a specific

period. It was used to determine the power density of each location's Weibull parameters. For a given period interval, the Weibull wind speed,  $v$ , probability density function was determined as  $f_w(v)$  and computed as:

$$f_w(v) = (k/a) (v/a)^{k-1} \exp -(v/a)^k \quad (1)$$

In Equation 1,  $a$  is the Weibull scale parameter,  $k$  is the shape factor (a dimensionless Weibull parameter),  $v_i$  is the speed of wind in the time stage,  $i$  and  $n$  are the numerical, non-zero data points for the characteristics of the wind. Next, we used the following equations to apply the parameter of maximum likelihood (MLH) and approximate the scale and shape parameters.

$$\begin{aligned} k &= [(\sum_{i=1}^n v_i^k \cdot \ln(v_i) / \sum_{i=1}^n v_i^k) - (\sum_{i=1}^n \ln(v_i) / n)]^{-1} \\ a &= (.5 \sum_{i=1}^n v_i^k)^{1/2} \end{aligned} \quad (2)$$

To obtain wind data at different incremental heights of ten meters from 20 m to 70 m AGL, extrapolation was used. Lastly, the data were analyzed to examine how changes in seasons impact the density of wind power.

### Power Law Usage for Vertical Extrapolation

The power law can be described as a functional relationship between two quantities such that as one quantity deviates, it results in the comparative proportionate shift in the variant quantity. The previous sizes and states of these quantities is irrelevant; in other words, the variation of one number is the power of the other. Our research was obtained using 10 m AGL as the standard height for wind data quantification. An analysis of how the speed of wind affects the wind power density at various heights applying the 1/7 power law [21]. Using power law was necessary to extrapolate wind speeds at specific heights. The power law's mathematical notation can be expressed as:

$$V_2 = V_1 (Z_2/Z_1)^a \quad (3)$$

In Equation 3,  $V_1$  represents the actual wind speed at height  $Z_1$ .  $V_2$  is the computed wind speed at the desired (extrapolated) height  $Z_2$ . The exponent  $a$  relates to the surface's roughness; a standard value of 0.142 is generally applied for standard locations.

Applying this extrapolation methodology, the wind speeds at various peaks range from 10 m to 70 m AGL with a computed variation of 5 m. It was determined that the speed of the wind increases by 34% at the peak of 70 m AGL compared to 10 m AGL. The increased wind speeds at the 70 m height effectively increases the potential wind power by 68%.

### Weibull Distribution

Weibull distribution computes the wind speed due to its two parameters. Mathematically it is explained as:

$$f(v) = (k/c) (v/c)^{k-1} \exp [-(v/c)^k] \quad (4)$$

In terms of a cumulative distribution function it is represented as:

$$f(v) = 1 - \exp [-(v/c)^k] \quad (5)$$

In Equation 5,  $v$  signifies the wind speed,  $k$  is a parameter which illustrates the data dispersion shape, and  $c$  is the scale parameter which has similar units of m/s to that of speed. Through applying the double logarithmic transformation on Equation 3, it can be regenerated as:

$$\ln \{-\ln[1-f(v)]\} = k \ln(v) - k \ln c \quad (6)$$

Equation 6 is a straight-line equation,  $y = ax+b$ . Plotting  $\ln(v)$  against  $\ln \{-\ln[1-F(v)]\}$ , results in a line that has a gradient  $k$  and  $-k$  long with the intercept along the y-axis. To calculate the density of wind power ( $W/m^2$ ), one should consider the wind power density (WPD), the wind speed frequency dispensation, and the cube root of the wind speed. For this reason, the density of wind power is usually considered as a major measure of the source of wind regarding the speed of the wind. As a result of drawing on the speed of the wind as the main variable, the average WPD is calculated as:

$$WPD = (\sum_{k=1}^n 1/2pv_i^3)/N \quad (7)$$

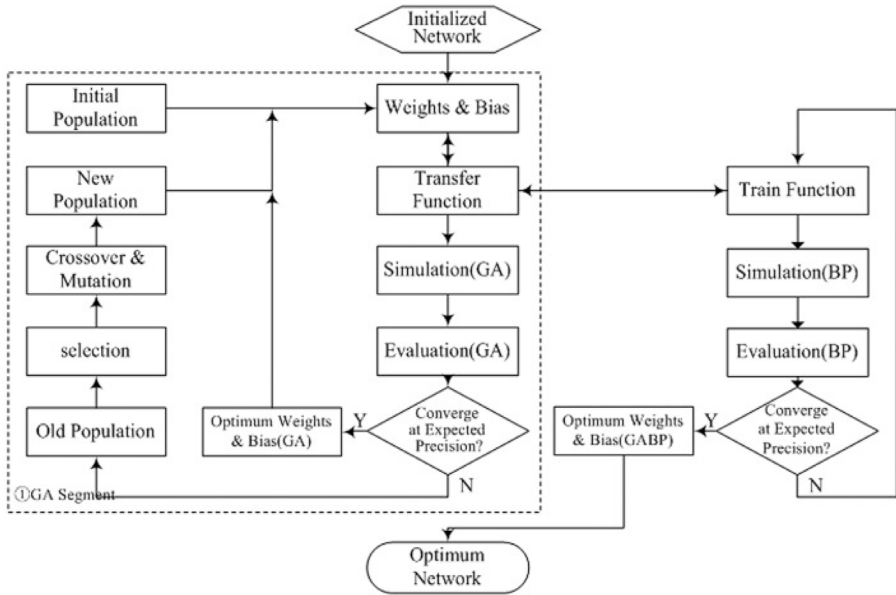
In Equation 7, the variable  $i$  represents the measured wind speed observed for each specific month.  $N$  is the sum of the data for that particular month over five years.

### Artificial Neural Network Forecast Prototype for Wind Power Density

The ANN has two prediction models, the back propagation neural network (BPNN) and the genetic algorithms (GA). The BPNN utilizes the weight update rule regarding gradient and techniques to predict the WPD. The model has the problem of a local minimum. The GA is a method that uses evolutionary biology such as natural selection, mutation, inheritance to solve a puzzle [6,23].

Research shows that the GA model performs much better compared to the BPNN model since it functions despite a lack of gradient information, therefore solving the problem of local minima.

Whitley, Stark, Hanson, together with Bogart in their different declarations, were first to implement the idea of bringing the ANN prediction model into a hybrid ANN (GA-BP) [24]. To predict the WPD, and to achieve (MAPE) a modern version was used.



**Figure 4. The Flow diagram of the hybrid GA-BP algorithm.**

The modified hybrid ANN was used to determine month-ahead predictions for WPD. Prior to populating data into the model, the standard settings used were 0-1 due to the variables utilized. The experiment used data from six years, 2010 through 2015 divided into two sets. To learn about the neural network-based model, they used 2010 through 2014 data with 2015 data used to assess and validate the model results. For ANN to work best, it was essential to choose the most suitable unit of layer of hidden neurons. It was concluded that one provided the required outcome. Log sigmoid was used for the hidden layer, and output layer used the linear activation function. The best neural network structure is 4-8-1, comprising of four-layer input, eight hidden and one by trial an output layer.

## RESULTS AND DISCUSSION

Our research probed the characteristics of selected variables to examine the ability of energy from wind to create power for electricity.

### Density of Wind Power

To evaluate the precision of the network, our research implemented an output from wind speed for one year and used the mean absolute percentage error (MAPE) for performance standards. The final MAPE attained using the GA-BP model from the three locations in Kuwait was measured as 2.11%. The data obtained was used to ascertain the locality with the top perspective in wind energy. Table 2 provides the locations, evaluation, and wind variables of the sites.

The wind generated electricity potential is influenced by the wind power density (WPD). According to Alamdari et al. the WPD can be described as a region's velocity together with the wind's distribution function [6]. Tables 3 and 4 provide categorizations of the wind power densities [6].

There are two significant results from the data analysis: 1) the outcomes show a positive correlation between wind direction and the influence of wind speed and vice versa; and 2) the critical variables in the meteorological data are the high values, the least values, the standard deviation (see Table 6), the mean and the median.

Figure 5 shows the wind speeds per time intervals at Wafra in 2014. Figure 6 displays the sample range for the rate of wind histogram for 2014. These Figures showcase 340 out of 368 samples derived from wind speeds ranging from 1 m/s to 6 m/s.

### Wind Speed Forecast

Next using the ANN together with the hybrid ANN-GA model, we describe the outcomes and the prior monthly forecasts for all there studied locations. Table 6 shows the differentiation of the two models for the forecasted wind speeds at every site. Figures 8 and 9 show the results for both prediction models for Wafra. The location shown in Table 6 indicates that the ANN model was envisaged by MAPE as 6.12% and 2.19% using ANN-GA. The ANN-based model at the KIA and Abdaly locations predicted MAPE values of 5.44% and 5.79% respectively. For the ANN-GA prototype results were 2.09% at KIA and 2.01% at Abdaly.

In Wafar, the power of the wind density per height in every location determined that the 70 m height had the maximum WPD and generated the maximum power. Using the ANN-GA model that can predict one-month prior wind



**Table 2. The three location zones and mean wind variables for 2015.**

<i>Sites</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Mean speed of wind (m/s)</i>	<i>Mean direction of the wind (degrees)</i>	<i>Mean wind highest speed (m/s)</i>
Wafra	29° 36' 34"	47° 34' 37"	3.66	223.76	11.45
KIA	29° 13' 18"	47° 57' 59"	4.44	243.60	12.39
Abdaly	30° 03' 58"	4° 41' 26"	2.73	207.67	10.77

**Table 3. Classification of wind power densities.**

<i>Wind speed (m/s) at 30m AGL</i>	<i>Wind energy density (W/m<sup>2</sup>)</i>	<i>Resource potential</i>
4.4 – 5.6	100-200	Fair
5.6 – 6.4	200-300	Moderate
6.4 – 7.5	300-500	Good
>7.5	>500	Excellent

**Table 4. The density of wind power at various heights AGL in Wb/m<sup>2</sup>.**

<i>Station name</i>	<i>WPD at 10 meter height</i>	<i>WPD at 20- meter height</i>	<i>WPD at 30- meter height</i>	<i>WPD at 40- meter height</i>	<i>WPD at 70- meter height</i>
Wafra	50.44	74.35	98.35	156.86	238.11
KIA	28.39	44.24	67.54	103.72	174.18
Abdaly	11.27	34.23	45.99	94.22	145.21

**Table 5. Associated evaluation of variables regarding wind.**

<i>S no.</i>	<i>Solar variables</i>	<i>Association</i>
1	Wind direction	0.8740
2	Top speed of the wind	0.7140
3	Top wind direction	0.7110
4	The density of wind power	0.8920

speed prediction, the study shows that the average speed at this location during the one-year period is between 3 m/s to 6 m/s. For the Weibull distribution, the mean WPD was between 70 W/m to 179 W/m at the standard height of 10 m AGL. For 70 m AGL it was determined that the WPD was from 160 W/m<sup>2</sup> to 293 W/m<sup>2</sup>, an increase of 82% from the normal height. In Kuwait, available wind power and electricity demand both peak during the sunny periods of the day. These forecasts can be used to predict the electrical generation capacity from wind turbine generators.

**Table 6. WAFRA data on quantitative evaluation of 2015.**

<i>Variable</i>	<i>Wind speed (m<sup>2</sup>/s)</i>	<i>Wind direction (degrees)</i>	<i>Wind maximum speed (m/s)</i>	<i>Wind maximum direction (degrees)</i>
Numeric value	368	368	368	368
Text values	0	0	0	0
Missing values	1	1	1	1
Unique values	61	159	123	135
Zero values	0	0	0	0
Most frequent	2.9	328	10.1	360
Minimum values	1.3	1	4.3	1
Maximum values	8.6	360	25.4	360
Median	3.05	320	10.95	144
Mean values	3.35	250.49	11.34	182.87
Standard deviation	1.33	114.50	3.36	130.24
2 $\sigma$	16	33	18	0
3 $\sigma$	5	0	3	0
4 $\sigma$	0	0	2	0

**Table 7.****The differentiation of forecast on the wind speed of ANN and ANN-GA.**

<i>Locality</i>	<i>ANN model</i>	<i>ANN-GA model</i>
Wafra	6.33%	2.18%
KIA	5.44%	2.07%
Abdaly	5.79%	2.00%

## CONCLUSION

In this research, we learned that wind, a renewable energy resource, provides sufficient energy for electrical power generation. Using the variables of wind speed, direction, and frequency distribution, wind energy can be analyzed in different locations in Kuwait. Both ANN and hybrid ANN-GA models were used to predict the wind speeds and the mean power from the wind density.

Figure 5. Wind speeds with times at Wafra in 2014.

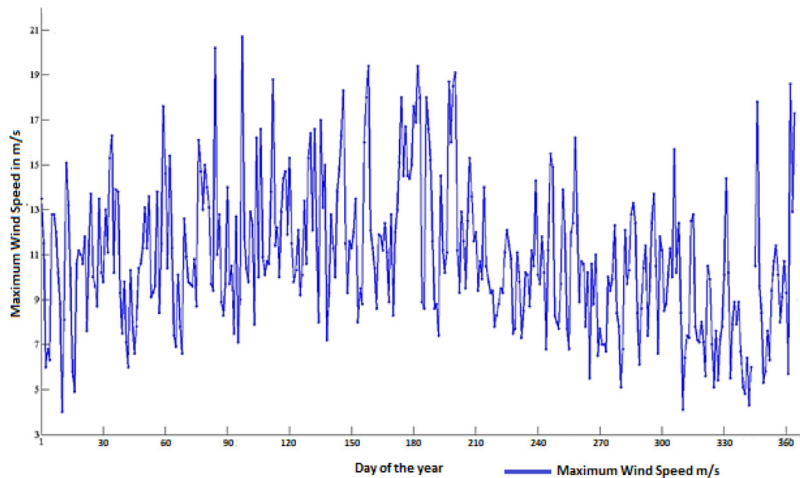
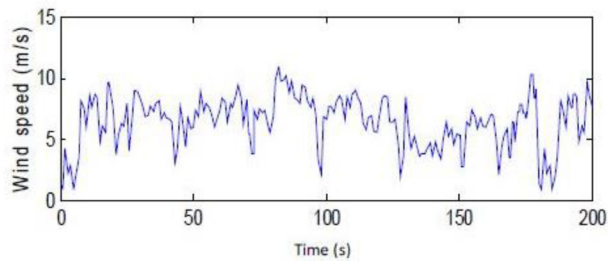


Figure 6. Maximum wind speeds at Wafra during 2014.

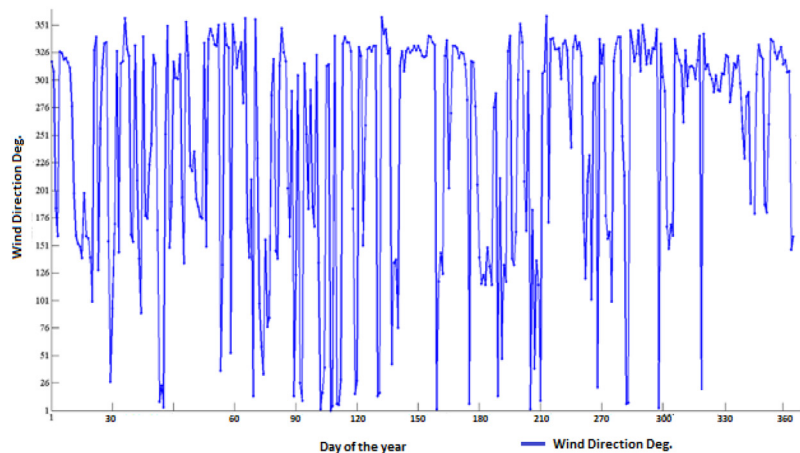
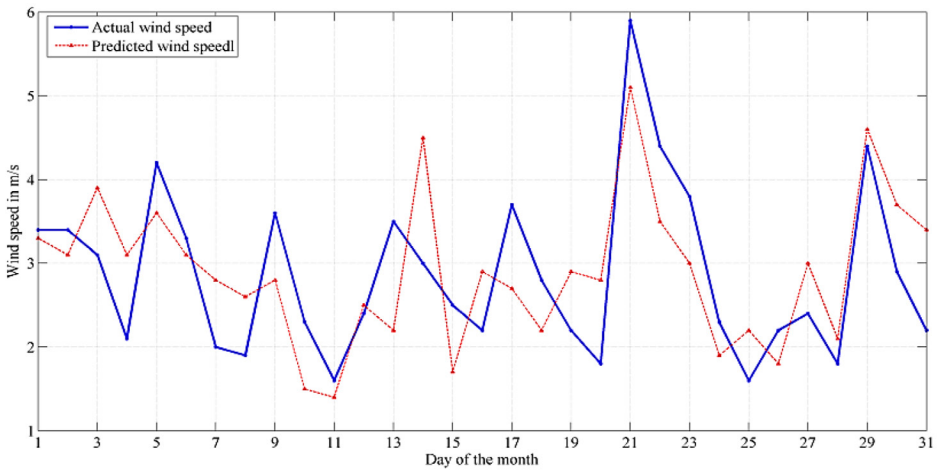
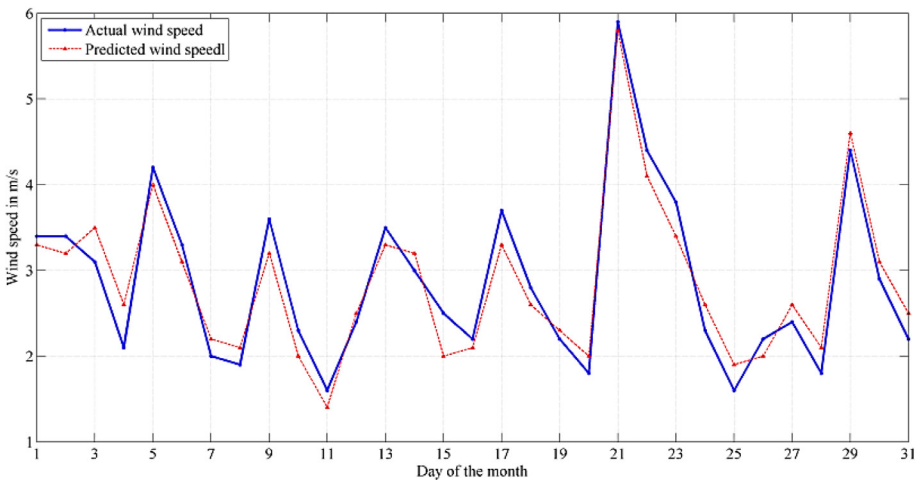


Figure 7. Wind direction at Wafra during 2014.



**Figure 8. Month before prediction of wind speeds using the ANN model for Wafra.**



**Figure 9. Month before prediction of wind speeds using the ANN-GA model for at Wafra.**

To evaluate the precision of the network, our study was performed with one output from the wind speed for one year and a mean absolute percentage error for performance standards. The final percentage error resulting from the GA-BP Model, was measured at 2.11%. The data obtained was used to ascertain the regions with the best available wind energy. Averaged over a year, the

wind speeds ranged from 3 m/s to 6 m/s in different parts of Kuwait. At 70 m height above the ground level, the wind power density ranged from 161 W/m<sup>2</sup> to 294 W/m<sup>2</sup>. We learned that RE sources, and wind in particular, have the potential to produce enough power to satisfy all of Kuwait's electrical energy requirements.

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# Comparative Analysis of Indirect Carbon Emissions from Electric Vehicles in India and France

*Caneon Kurien, Ajay Kumar Srivastava and Emeric Molere*

## ABSTRACT

The increasing levels of environmental pollution from vehicles that consume fossil fuels have shifted the focus of the transportation sector to electric vehicles. Zero emission claims by many electric vehicle manufacturers have increased the popularity of electric vehicles (EVs) among industrial and academic researchers. Those claims of reduced emissions by EV manufacturers are not necessarily true in countries that rely primarily on fossil fuel-fired power plants to generate electricity. The use of EVs in countries that depend on fossil fuels to generate electricity shifts emissions from the operation stage to energy generation stage.

In this article, a comparative study has been conducted on the energy mix of one developing country (India), which relies on fossil fuels for energy generation and a developed country (France), which relies mostly on renewable energy (RE) sources. Equivalent carbon dioxide (CO<sub>2</sub>) emissions from EVs for both cases have been calculated and are compared with emissions from vehicles that use fossil fuels. The results of our study show that the introduction of EVs in present energy mix scenario in India actually increases total CO<sub>2</sub> emissions. The energy mix requirements needed prior to introducing EVs are proposed to ensure a 50% reduction of overall emissions. The estimates were developed by conducting reverse calculations

## INTRODUCTION

The exhaust gases released by fossil fuel-based vehicles directly impact human health and the environment [1,2]. The emissions from the transportation sector globally account for 54% of carbon monoxide, 30% of nitrogen oxides and 47% of hydrocarbons [3,4]. In the European Union (EU), the automotive industry is the second largest source of greenhouse gas emissions (GHGs) after the power generation industry [5,6]. In the last two decades the world's



emissions from automotive vehicles has increased by more than 20% [7,8]. Introducing alternate fuels and pre-and-post treatment strategies have reduced the level of emissions considerably but the increasing the number of vehicles has neutralized the impacts of installing emission control systems [9,10]. The crude electric carriage technique was used by a Scottish researcher in 1832 for developing the first electric vehicle gained popularity in the early decades of 19<sup>th</sup> century. Internal combustion engines took over the markets owing to their better performance which led to the disappearance of most electric vehicles by 1935 [11,12]. The initial signs of rising pollution levels and global climate change in 1960s spurred research into the feasibility of EVs as a possible alternative for fossil fuel-based vehicles [13,14].

Electric motors are simpler than internal combustion engines. The major components include the direct current (DC) controller, DC motor, potentiometer and battery (lithium ion or lead acid). The potentiometer connected to the acceleration pedal of the vehicle transmits signals to the DC controller which controls the power supply from the battery to DC motor. Two potentiometers are linked to the acceleration pedal for safety purposes so that the controller can be programmed to accept signals only after verifying the input data from both potentiometers.

### **Challenges Hindering the Acceptance of Electric Vehicles**

While the technologies needed for electric vehicles are proven other challenges hinder broader adoption. The lengthy time required to recharge a battery is one of the major challenges faced by the electric vehicles [15-17]. The comparative short travelling distances between battery charges is another major factor affecting the acceptance of EVs in global markets. Other challenges include higher capital cost and the lack of battery recharging facilities and infrastructure [18-20]. Market acceptance of EVs can be improved by reducing the cost of batteries as they can account for more than half the price of the vehicle [21]. Most EVs use lithium-ion (LI) batteries owing to their higher power densities and longevity compared to lead-acid batteries. Limited lithium reserves pose a threat to increased use of EVs since shortages of lithium could eventually cause price increases. Battery management systems are also employed in most of EVs to record service life, charge status and battery effectiveness [22]. At the early stages of development, DC motors were used widely in EVs but the wear on commutators and brushes reduced effectiveness, leading to the application of alternating current (AC) motors with higher power densities [23].

Another major challenge is the development of electronic systems (e.g., diodes and capacitors) that can withstand the higher temperatures and vibration

that occur during vehicle operation [24,25]. Major modifications must be made to the existing power grids since they would be unable to withstand the power demand if a number of vehicles are charged simultaneously. The economic feasibility of EVs is dependent on the price of batteries, charging infrastructure and fuel availability [26-28]. The service life of the batteries used in EVs can be a problem. Previous studies have noted that the battery life is less than the vehicle life which depreciates the price of used EVs [29,30]. Zero emissions claims by EV manufacturers can be misleading since battery recharging is dependent on the local power generation systems. Achieving zero emissions is possible only when there is no electricity being supplied by fossil fuel-fired sources. Hence types and quantities of emissions vary depending on how the electricity is generated [31,32].

## ENERGY SCENARIOS IN FRANCE AND INDIA

Next we provide a comparative analysis of the indirect carbon emissions from electric vehicles for France and India. France, one of the EU's largest countries, is also one of the world's largest exporters of electricity since its cost of electricity generation is quite low. As shown in Figure 1, fossil fuel-based power plants provide less than 10% of the country's total electricity production. The carbon emissions from generating electricity in France are low since the country relies on nuclear and RE-based power plants for power generation. It would be appropriate to introduce EVs in France since the country produces a surplus of electricity from less carbon emitting sources; hence the level of indirect emissions will be negligible. The French government has also introduced energy policies to reduce the pollution caused by vehicles. According to the International Energy Agency, the country emitted 290.5 MT of CO<sub>2</sub> from fuel combustion in 2015 of which 40% was from the transportation sector.

As an initiative to reduce the automotive emissions from fossil fuel powered vehicles, the French central government has introduced various subsidies for electric vehicles [33]. The cost of conventional gasoline and diesel fuels increased in price by 15% and 23%, which helps compensate for the EV subsidies. The French government provides a subsidy of 6,000€ for the purchase of vehicles that emit less than 20 g of CO<sub>2</sub>/km. This applies to most EVs and alternately-fueled vehicles. In addition, when owners of older diesel vehicles exchange their vehicles for a battery electric vehicle (BEV), they receive an extra 4,000€. Infrastructure to support EVs has improved as the number of public recharging locations has increased from 2,000 in 2014 to 16,000 in 2017.

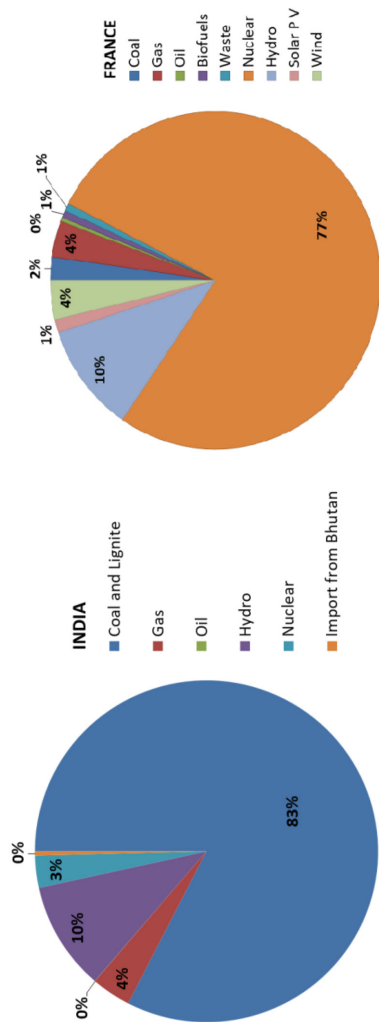


Figure 1.  
Sources of energy used for electricity generation in France and India.

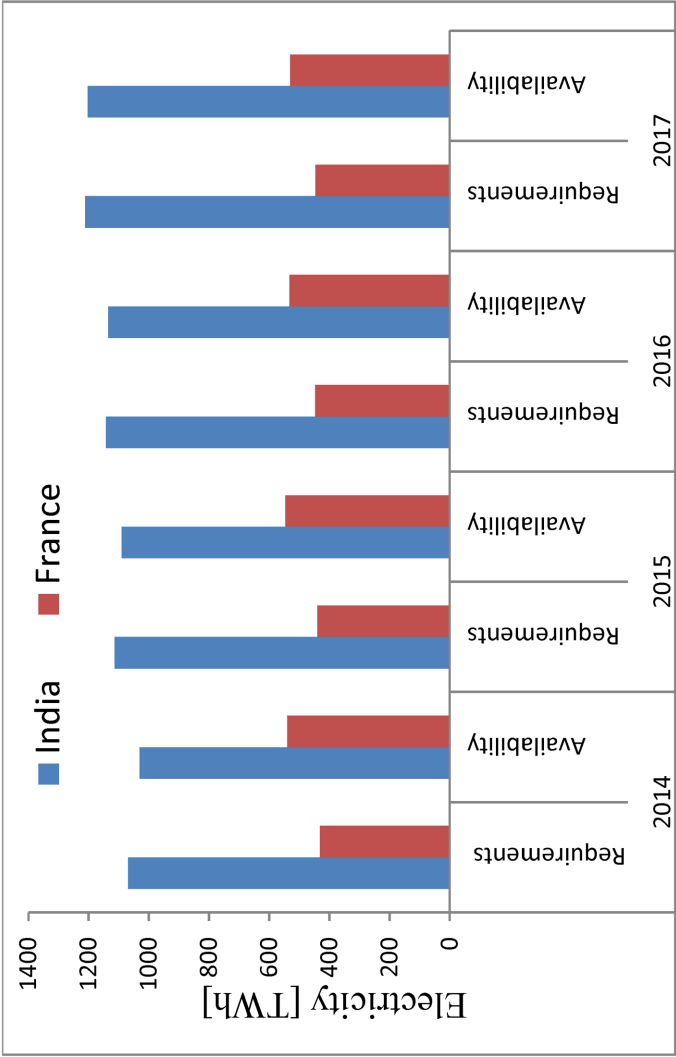


Figure 2. Electricity requirements and availability in India and France from 2014 to 2017 [27].

These measures prove that French government has policies in place to promote electric vehicles. However, in 2017 only 1.2 % of the vehicles in France were BEVs. Customers are reluctant to purchase BEVs as some perceive internal combustion vehicles (ICVs) to have better performances.

India, a developing country, ranks third in the world among those with higher carbon emissions after China and the U.S. [34]. India is dependent on fossil fuels which account for most of the energy used for electricity production. India's fossil fuel-fired power plants represent about 64% of total installed electricity generation capacity. The electricity generation target for 2018-19 showed that about 86% (1,091,500 million kW) of electricity generation is from conventional fossil fuel sources and only 14% of the total electricity generation is from RE sources [35]. According to the Ministry of Power, India produces a deficit amount of electricity for meeting its present electricity requirements [27]. Figure 2, compares electricity requirements and availability in India and France from 2017 to 2017 [27]. Due to aging infrastructure which creates energy losses and increased carbon emissions, the transmission and distribution losses in India's electrical system are roughly 19.5% [36]. For India, the introduction of more EVs will increase the amount of carbon emissions since the electric grid is mainly dependent on fossil fuel-based resources [37].

## INDIRECT CARBON EMISSIONS FROM ELECTRIC VEHICLES

Energy stored in the batteries of electric vehicles is used primarily for propulsion. The distance travelled by a fully charged EV is less than that of fully-fueled gasoline and diesel powered vehicles [25]. The indirect carbon emissions from EVs depends on the power generation sector which is variable [16]. Hence the zero emission claims of EV manufacturers are true only for regions with electricity generation from carbon-neutral sources.

Indirect carbon emissions from EVs in India and France are compared in this study to highlight the importance of the energy mix in managing emissions. The equivalent carbon emissions are calculated by considering vehicle energy consumption per km and power sector CO<sub>2</sub> emissions per kW. The equivalent carbon emissions per km from EVs can be evaluated using Equation 1, where  $C_{ev}$  is the carbon emissions from EVs in grams of CO<sub>2</sub> per km,  $E_{ev}$  is the energy consumed by the EVs in Wh/km,  $C_{electricity}$  is the carbon emissions during electricity generation from power plants in grams of CO<sub>2</sub>/Wh, and  $L_T$  is the grid's percentage of transmission and distribution losses [37].

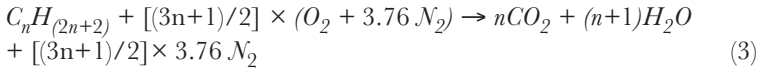
$$C_{ev} = EC_{ev} \times [C_{electricity} (1 - L_T)] \quad (1)$$

The CO<sub>2</sub> emissions that occur during electricity generation are calculated using Equation 2, where  $x_i$  is the emission from the energy source during electricity generation in kg of CO<sub>2</sub> per kWh, and  $w_i$  is the percentage share of the particular energy source used for power generation. The carbon emissions during electricity generation from coal, oil, gas and bio-energies are 1.03 kg CO<sub>2</sub>/kWh, 0.63 kg CO<sub>2</sub>/kWh, 0.49 kg CO<sub>2</sub>/kWh and 0.98 kg CO<sub>2</sub>/kWh [38].

$$C_{\text{emission\_electricity}} = \sum_{i=1}^n x_i \times w_i \quad (2)$$

## CARBON EMISSIONS FROM FOSSIL FUEL POWERED VEHICLES

The carbon emissions from fossil fuel powered vehicles can be calculated based on the volume of fuel consumed by the engine. The combustion equation for hydrocarbons is shown in Equation 3 using both the gasoline octane group (i.e.,  $n = 8$ ) and the diesel hexadecane group ( $n = 16$ ). The mass of CO<sub>2</sub> rejected and the mass of fuel consumed can be calculated using Equations 4 and 5, where  $m(\text{CO}_2)$  is the mass of CO<sub>2</sub> rejected in grams and  $m(\text{C}_n\text{H}_{2n+2})$  is the mass of fuel consumed in grams.



$$m(\text{CO}_2) = n \times \text{molecular weight} = n \times 44 \quad (4)$$

$$m(C_nH_{(2n+2)}) = [n \times 12] + [(2n+2) \times 1] \quad (5)$$

The mass of CO<sub>2</sub> rejected per litre of the fuel can be evaluated using Equation 6, where  $r$  is the ratio of the mass of CO<sub>2</sub> rejected to the mass of fuel consumed and  $\rho$  is the density of the fuel. Vehicle fuel densities are 0.74 kg/l for gasoline and 0.85 kg/l for diesel.

$$M_{\text{CO2per\_litre}} = [m(\text{CO}_2)/m(C_nH_{(2n+2)})] \times \rho_{\text{fuel}} \quad (6)$$

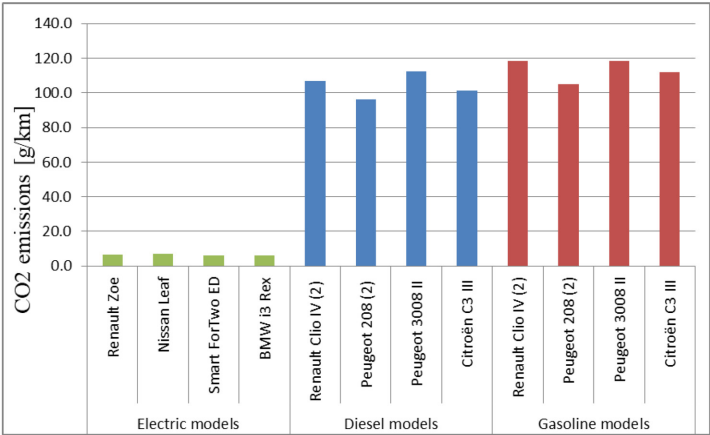
## ANALYSIS OF EV CARBON EMISSIONS IN FRANCE AND INDIA

The carbon emissions from electric and fossil fuel powered vehicles available in France were conducted by considering the specifications of commercially available vehicles categorized as diesel, gasoline and electric vehicles. The specifications of the vehicles considered for the analysis are shown in Table 1.

**Table 1.**  
**Power consumption and carbon emissions from vehicles in France.**

<i>Sl.No</i>	<i>Vehicle name</i>	<i>Fuel type</i>	<i>Consumption</i>	<i>Emissions (g/km)</i>
1	Renault Zoe	Electric	14.6 kWh/100km	6.7
2	Nissan Leaf	Electric	15 kWh/100km	6.9
3	Smart ForTwo ED	Electric	12.9 kWh/100km	5.9
4	BMW i3 Rex	Electric	13.5 kWh/100km	6.2
5	Renault Clio IV 1.5	Diesel	4.0 litre /100km	106.8
6	Peugeot 208 (2)	Diesel	3.6 litre /100km	96.1
7	Peugeot 3008 II	Diesel	4.2 litre /100km	112.1
8	Citroën C3 III	Diesel	3.8 litre /100km	101.5
9	Renault Clio IV (2)	Gasoline	5.2 litre /100km	118.6
10	Peugeot 208 (2)	Gasoline	4.6 litre /100km	104.9
11	Peugeot 3008 II	Gasoline	5.2 litre /100km	118.6
12	Citroën C3 III	Gasoline	4.9 litre /100km	111.7

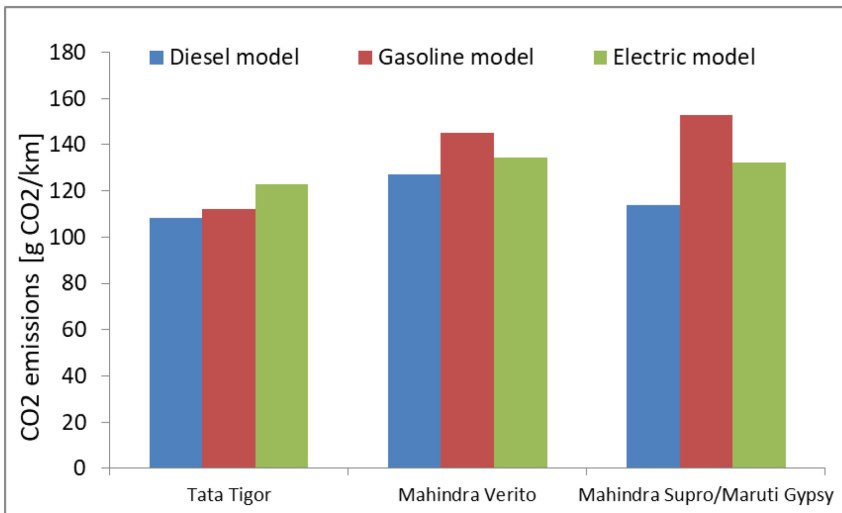
The carbon emissions from EVs in France are very low, less than 10% of the emissions from the gasoline and diesel-powered vehicles. The emissions from the categories of electric, diesel, and gasoline vehicles in France are shown in Figure 3. The levels of carbon emissions are reduced by greater use of EVs. The carbon emissions from EVs and fossil fuel powered vehicles in India is calculated by considering the specifications of vehicles in each category as shown in Table 2. The carbon emissions from vehicles in India vary from those in France. The indirect carbon emissions from EVs are higher than those of the gasoline and diesel-powered vehicles (see Figure 4).



**Figure 3.** CO<sub>2</sub> emissions from EVs and fossil fuel vehicles in France.

**Table 2. Power consumption and CO<sub>2</sub> emissions from vehicles in India.**

<i>Sl.No</i>	<i>Vehicle name</i>	<i>Fuel type</i>	<i>Consumption</i>	<i>Emissions (g/km)</i>
1	Tata Tigor EV	Electric	12.0 kWh/100km	122.5
2	Mahindra eVerito	Electric	13.1 kWh/100km	134.5
3	Mahindra eSupro	Electric	12.9 kWh/100km	132.1
4	Tata Tigor 1.05	Diesel	4.0 litre /100km	108.0
5	Mahindra Verito 1.5 D2	Diesel	4.8 litre /100km	127.0
6	Mahindra Supro LX	Diesel	4.3 litre /100km	113.6
7	Tata Tigor 1.2	Gasoline	4.9 litre /100km	112.4
8	Mahindra Verito 1.4	Gasoline	6.4 litre /100km	145.2
9	Maruti Gypsy 1.0	Gasoline	6.7 litre /100km	152.8

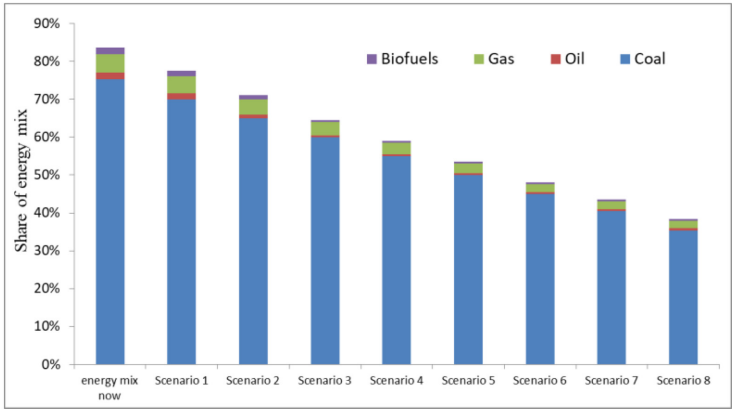
**Figure 4.**

**Indirect CO<sub>2</sub> emissions from EVs and fossil fuel vehicles in India.**

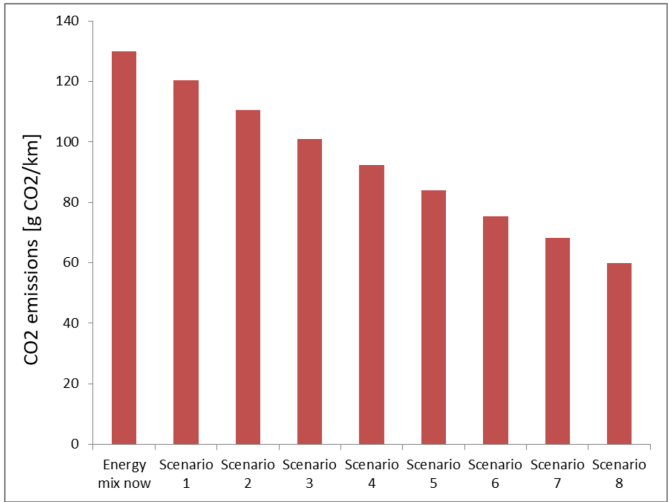
The indirect carbon emissions from EVs are higher in India since the country relies heavily on fossil fuel-powered plants for electricity generation which increases total emissions. Since about 83% of its electricity generation is from fossil fuel-fired power plants (see Figure 1) an analytical study was conducted using different energy mix scenarios. Reverse calculations were conducted for reducing the percentage share of fossil fuels in the power sector to determine the minimum energy mix that would lower indirect carbon emissions from EVs to 50% of the emissions from fossil fuel-powered vehicles. Reverse percentage



calculations assume a given percentage of an amount which is used as a basis to estimate predicted amounts. Our study assessed eight different scenarios in which the share of fossil fuel sources is reduced by 5% (see Figure 5). The average emissions from gasoline and diesel vehicles are 120 g/km. It was determined that indirect carbon emissions from EVs can be reduced to 60 g/km if the share of the fossil fuels in the energy mix for power generation is 40% (see Figure 6).



**Figure 5. Share of fossil fuels in the energy mix used for a scenario analysis to reduce indirect carbon emissions from EVs in India.**



**Figure. 6. Scenario analysis to determine the minimum share of energy mix required to reduce indirect carbon emissions from EVs in India to 60 g/km.**

## CONCLUSION

The demand for the fossil fuel-powered engines has increased in the automotive industry due to their higher thermal efficiency and performance characteristics. Increasing pollution levels in urban areas and the initial signs of global climate change have resulted in stringent GHG emission regulations. The use of alternate fuels and the use improved cylinder combustion designs have reduced the toxicity of exhaust emission somewhat, but not enough to meet the emission regulation requirements. Post treatment emission control systems have the ability to reduce the emissions to acceptable levels but there are challenges involved in the implementation of these systems. Electric vehicles have been largely overlooked by the automotive industry yet research is shifting its focus from fossil fuel-powered vehicles to EVs. The zero emission claims of some EV manufacturers have been used to market EVs. However, such claims are true primarily for regions which do not depend on fossil fuel-based power plants to generate electricity.

This article discusses a comparative analysis of the indirect carbon emissions from EVs in France and India. The results of our study showed that the introduction of EVs in France have potential to reduce carbon emissions by more than 90% as compared to carbon emissions from fossil fuel powered vehicles. In India, however, the indirect carbon emissions from EVs will be greater than the carbon emissions from gasoline and diesel-powered vehicles.

The major reason for increases in indirect carbon emissions is that the fossil fuel-fired power plants provide more than 80% of the electricity generated in India. Hence reverse calculations were conducted to estimate the maximum share of fossil fuels in the energy mix required to reduce indirect carbon emissions by 50%. The results of our study show that the indirect carbon emissions from EVs in India can be reduced to half (60 g/km) if the share of fossil fuels is less than 40% of the total energy mix. The mix of fuels for electricity generation will be the determining factor for achieving the zero emission claims of EV manufacturers. Countries that rely on fossil fuel-based power plants must consider development of renewable or clean energy generation prior to investing in programs that promote the introduction of EVs.

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# Natural Gas Consumption, Economic Growth and Trade in Canada: Evidence from Time and Frequency Domain Causality Approaches

*Dervis Kirikkaleli, Seyi Akadiri, Festus Bekun and Andrew Alola*

## ABSTRACT

In this study, the causal effects of natural gas consumption and total trade on gross domestic product (GDP) are explored for the case of Canada, covering the period from 1965 to 2017. Our research objective was to test whether or not natural gas (NG) consumption predicts total trade and economic growth in Canada by examining the causal relationships among NG consumption, total trade and economic growth. The causality tests reveal that there is evidence of a causality running from NG consumption and total trade to GDP, implying that changes in Canada's NG consumption and total trade lead to significant changes in GDP. It is important to mention that both time and frequency domain causality tests provide consistent outcomes at different levels of significance and frequency. Additionally, to capture the cointegration equation among the time series variables, the Hatemi-J cointegration test is employed. The cointegration technique allows two possible endogenous regime shifts in the cointegration relationship, revealing that cointegration exists among the time series variables with endogenous structural breaks.

Our results indicate the existence of an equilibrium relationship, implying that both natural gas consumption and total trade are key drivers of economic output in the Canadian economy. We conclude that energy and environmental policies that are aimed at encouraging the use of both renewable and non-renewable energy sources should be pursued in Canada and elsewhere.

## INTRODUCTION

Considering its robust production and huge supply of resources, Canada's natural gas (NG) industry has provided reliable and affordable NG to its citizen-

ry for many years. Currently, Canada exports natural gas to the United States. From 2007 onwards, there has been a persistent reduction in Canada's NG exports to the U.S. The U.S. has developed its own supplies of NG products, to the extent that the U.S. is currently a net exporter of NG for the first time in over six decades. Despite, the trends in NG exports to the U.S., there was an increase in the Canadian NG exports to the U.S. from 2016 to 2017.

Canada is a unique country to study in regard to the interactions between natural gas consumption and total trade and their impacts on real output. This is due to Canada being one of the world's largest producers of NG and having substantial reserves (about 1.23 trillion ft<sup>3</sup>)[1]. This represents a 30-decade supply based on existing consumption levels and newly-introduced technologies. Canada's NG supplies substantially exceed its internal demand. This has positive implications for the country in terms of potential exports and related employment opportunities.

Over the last decade, the market for natural gas products in Canada has changed. This is due to inadequate NG market diversification, which created challenges for producers. The irony of these market transitions is that Canada's primary buyer (the U.S.) has become its major competitor. How did this change in market dynamics occur? Over a decade ago, improvements in multi-level hydraulic fracturing and horizontal drilling enabled U.S. natural gas producers to increase their production by more than 40% [1]. Since 2011, the U.S. has become one of the world's top producers of NG. In North America, where NG prices have been depressed due to regional oversupply, exports of NG from Canada to the U.S. have generally declined, particularly to the eastern U.S. states. Increasing production of NG in the central regions of the U.S. has provided domestic producers with a cost advantage due to lower transportation costs that result from shorter distances to points of consumption. The U.S. is increasing NG exports to the Canadian provinces of Quebec and Ontario, replacing the domestically produced NG previously supplied from western Canada.

The global demand for natural gas is anticipated to increase by 45% by 2040. This will primarily be caused by the rapid growth of Asian economies. Canada's NG resources are capable of meeting their anticipated growing energy demands as it is among the world's top five largest producers of NG [1]. Fluctuations in NG production, market conditions, and reduced exports to the U.S. affect Canada's NG markets. Its implications on Canada's real output and income motivated us to conduct this study.

This study contributes to the natural gas consumption-economic growth relationship in the following ways: to the best of our knowledge, there are few or

no studies about the interrelationship and interconnectedness among Canada's natural gas consumption (NGC), total trade and economic growth. Examining the impact of NGC on economic growth in Canada provides a valuable contribution. Most of the studies in the energy literature fail to focus on Canada's NGC-trade-economic growth nexus.

Research studies found in the energy literature that are related to Canada instead focus on the relationships among greenhouse gas emissions (GHG), energy consumption and economic growth [2-5]. Perhaps, authors who have studied NG (e.g., Rowse) have perceived NG to be a relatively inexpensive commodity irrelevant to total trade and the economic growth of Canada [5]. This perception limits study of the potential impacts on economic growth and its multiplying impacts on the global economies. Alternatively, authors in the field of energy may have preferences for other macroeconomic variables. One objective of our study is to provide clarification and fill the existing gaps found in the empirical and methodological literature.

To the best of our knowledge, there are few studies that have specifically examined the direction of the causality among NGC, total trade and real income in a logical framework using Canada as a case study. Our research objective was to test whether or not NG consumption predicts total trade and economic growth in Canada. To achieve this, we began by confirming the stationarity properties of the series using the Dickey-Fuller generalized least squares (DF-GLS) and Zivot and Andrews (ZA) unit root test, which account for structural breaks [6]. Then, we proceeded to examine whether a long-run equilibrium relationship exists using the Hatemi-J cointegration test [7]. To detect the direction of causality, several tests were employed including the Toda and Yamamoto frequency domain causality (FDC) test, spectral Breitung and Candelon (BC) causality and the gradual shift causality (GSC) test proposed by Nazlioglu, Gormus and Soytaş [8-10]. The latter accounts for possible structural break(s), since it is paramount in time series empirical studies to control for structural or regime shifts that might affect empirical estimations and lead to spurious empirical results such as jumps, cycles or breaks.

Our study considered the direction of the causal relationships among NGC, total trade and economic growth for the case of Canada. We examined whether an increase and/or decrease in NGC predicts total trade and economic growth and vice versa using three causality testing approaches, namely, the frequency domain causality test-spectral BC causality test and the gradual shift causality that account for possible structural breaks [8-10]. Based on the results of the Hatemi-J cointegration testing approach, which accounts for two possible endogenous regime shifts in the cointegrating relationship, the



existence of a long-run equilibrium relationship among the series is clearly revealed. For Canada the causality analysis results show evidence of casualty relationships running from NGC to economic growth and from total trade to economic growth. These results indicated that changes in Canada's NGC and total trade significantly led to changes in long run economic growth. The frequency domain causality tests provided consistent outcomes at different levels of significance and frequency levels.

This study is organized as follows: we review the literature on the natural gas-economic growth nexus, analyze data using the econometric method, present the estimation results, and discuss the findings. We conclude by offering policy suggestions.

## RELATED STUDIES

Generally, the relationship between energy consumption and economic growth has been conceptualized to widely reflect four types of hypotheses in the extant literature. Specifically, Ozturk and Al-Mulali stated that these hypotheses are growth, conservation, feedback and neutrality [11]. Other studies have been conducted by disaggregating sources of energy consumption, which include non-renewable energy sources such as nuclear energy and natural gas, and renewable sources such as wind power, geothermal and solar. The empirical evidence from these studies has consistently underpinned the nature of the impact of the energy mix for different case studies [12-16]. In the context of NGC, studies have revealed that the aforementioned hypotheses are reasonable [11, 17-24].

Interestingly, the nexus between natural gas consumption and economic growth was recently considered by Aydin using a Granger causality analysis in the frequency domain approach [21]. Having employed the top 10 NG-consuming countries for the period 1994-2015, the results indicated that NGC exhibited a significant and positive impact on long run economic growth. Additionally, the causality running from economic growth to NGC was observed to be temporary for Germany, but permanent for the United Kingdom (UK) and Thailand. However, the causality running from NGC to economic growth in Thailand was determined to be temporary. Importantly, Aydin found that energy security and dependence, economic growth, and a reduction in carbon emissions in the examined countries could be achieved by increasing the consumption of NG [21]. This is true when NG displaces either oil or coal in a combustion process as less greenhouse gases are emitted. Similarly, an earlier

study by Desstek incorporated trade openness, NG consumption, and economic growth in a multivariate production model approach for a panel of 26 Organization for Economic Co-operation and Development (OECD) countries [20]. Moreover, unidirectional and bidirectional causality from NGC to gross domestic product (GDP) growth affirm the growth hypothesis in the short-run and the conservative hypothesis in the long-run, respectively. In addition to the causality result, the study observed that trade openness is cointegrated with endogenous structural breaks, while the impact of NGC on the GDPs of OECD countries is significant and positive in the long run.

Li et al. examined the case of the Republic China, the world's third-largest natural gas consumption market [22]. The study revealed that NGC has a significant role in China's economic growth and the potential to directly and indirectly change production and industrial processes. Li et al. employed a panel quantile regression to examine the nexus between NGC and economic growth for 30 Chinese Provinces between 2000 and 2014 [22]. Their study revealed that the higher the level of economic output, the greater the marginal effect of NGC on economic growth. Hence, in the case of China which has different economic scales within its provinces, the impact of NGC is variable.

Studies by Akadiri et al. using Saudi Arabia as a case study, found that natural gas consumption prevails over the long term and increases future exports [23]. While investigating the relationship between NGC and economic growth, Fadiran et al. conducted a panel study of 12 European countries, among them the top ten using NG vehicles [24]. Panel cointegration and the long-run vector error correction model analysis confirmed a long-run impact of NGC on economic growth [24]. The study maintained that the growth hypothesis in Austria, Bulgaria and Switzerland is significant, while the conservation hypothesis is significant for the United Kingdom (UK) and Italy. This is consistent with Li et al. on the dynamic nexus between China's NGC and economic growth [22].

Using a bootstrap-corrected causality test for the G-7 countries, Kum et al. examined the relationship between natural gas consumption, economic growth, and capital for the period from 1970 to 2008 [17]. Their study found a unidirectional causality from NGC to economic growth for Italy, but a reverse causality for the UK. However, a directional causality from NGC to economic growth was observed for France, Germany and the U.S. Until now, relevant studies have been conducted to examine the relationship between NGC and economic growth by incorporating trade openness, fixed capital formation, capital and labor force, among other macro- and socio-economic variables. For instance, different cases have been employed in conducting similar investigations: Apergis and Payne employed 67 countries for a related panel study [25];

Shahbaz, Arouri and Teulon investigated a similar case for Pakistan by employing the autoregressive distributed lag (ARDL) approach for the period 1972Q1-2011Q4 [26]; while other researchers considered the cases of Malaysia and Iran in separate but related studies [18-19].

## DATA AND METHODOLOGY

In this study, the role of natural gas on economic output in Canada is examined in a multivariate framework with total trade ( $TT$ ) being an additional variable. Our study improves on the several previous studies [23,27,28]. It spans from 1965 through 2017 on an annual frequency basis and uses real  $GDP$  and total trade (the sum of exports and imports), all valued in constant 2010 U.S. dollars. Both are used as proxies for economic growth. Natural gas consumption ( $NGC$ ) is taken in dry billion cubic meters. Data for the variables  $TT$  and  $GDP$  were sourced from the World Bank, while  $NGC$  was obtained from the U.S. Energy Information Administration (USEIA) database.

### Model Specification

The functional form that encapsulates the relationship between the variables under review is shown in Equations 1 and 2:

$$GDP_t = (NGC_t, TT_t) \quad (1)$$

$$\ln GDP_t = \alpha + \beta_1 \ln NGC + \beta_2 \ln TT_t + \varepsilon_t \quad (2)$$

In Equations 1 and 2,  $GDP$ ,  $NGC$ , and  $TT$  represent economic growth, natural gas consumption and total trade, respectively.  $\alpha$  denotes the constant terms,  $\beta$ s are the partial slope parameters to be estimated and,  $\varepsilon_t$  is the stochastic term. The subscript,  $t$ , stands for the time frequency dimension, which spans the period from 1965 through 2017. The study's *a priori* expectation is that both  $\beta$ s  $> 0$  are positive. In other words, an increase in  $\beta_1$  increases economic output. A similar trend is expected for  $\beta_2$ , as  $TT$  is expected to spur increases in  $GDP$ .

This study follows three paths on its empirical trajectory: 1) examining stationarity properties of the variables under review via the DF-GLS plus a unit root test to account for a single structural break; 2) investigating the equilibrium long-run relationship via the Hatemi-J cointegration test; 3) detecting the direction of causality using several tests that included the gradual shift causality test and the frequency domain causality test-spectral BC causality test [6, 8-10].

Prior to the investigating the direction of the causality analysis, the long-run equilibrium relationship between the variables was examined. The econometrics literature has well documented cointegration tests [29-32]. However, none of these tests account for possible structural break(s). An incorrect assumption of no possible structural break(s) leads to spurious regression, given that most macroeconomic/financial series possess jumps, cycles or breaks. Newer cointegration tests have emerged in econometric literature, such as Gregory and Hansen that account for a single shift structural break [33]. The Gregory and Hansen test possesses three alternative hypotheses: 1) the shift in the intercept (Equation 3); 2) the case where the shift is in both intercept and trend (Equation 4); and, 3) the shift is in the intercept and the slope coefficient (Equation 5). These models are presented below:

$$y_{1t} = \mu_1 + \mu_2\phi_{t1} + \alpha'y_{2t} + e_p \quad t = 1, \dots, n \quad (3)$$

Equation 4 forms the Gregory and Hansen's cointegration test that accounts for both intercept and trend.

$$y_{1t} = \mu_1 + \mu_2\phi_{t1} + \beta_t + \alpha'y_{2t} + e_p \quad t = 1, \dots, n \quad (4)$$

The most widely used form of the Gregory and Hansen's test technique is the version that allows for a shift in both the intercept terms and slope coefficient, as expressed in Equation 5.

$$y_{1t} = \mu_1 + \mu_2\phi_{t1} + \alpha'y_{1t} + \alpha'y_{2t}\phi_{t1} + e_p \quad t = 1, \dots, n \quad (5)$$

The creation of a dummy variable helps to account for structural changes in the fitted model as shown in Equation 6.

$$\phi_{t1} = 0, t \leq nt; 1, t > nt \quad (6)$$

In Equation 6, 0 and 1 symbolize the trimming of the change point. Andrews asserts that trimming generally ranges around  $(0.15n, 0.08n)$ , as expressed in Equations 1, 2 and 3 [34]. The Gregory and Hansen approach uses three test statistics of the ADF, Za and Zt tests, respectively, to substantiate the null hypothesis of no cointegration. However, these tests cause misspecification of the cointegration test when there is an unknown structural break [33]. This creates invalid estimates in the regression. To circumvent these flaws, Gregory and Hansen proposed a modified version of the ADF, Za, and Zt tests statis-

tics to perform cointegration analysis among variables [33]. Furthermore, the Hatemi-J advanced cointegration test accounts for two structural break dates. The threshold cointegration test is a combination of the Gregory and Hansen cointegration and Hatemi-J cointegration tests.

This study proceeds next to detect the direction of causality given that the regression does not depict the causality. The causality test is necessary to develop a policy framework. The current study adopts the Toda and Yamamoto (TY) test, modified version of the Wald test, rather than the traditional causality test [8,32]. The TY has some merits compared to the traditional Granger causality test. The TY test provides more consistent and robust estimates in the presence of a mixed order of integration among series, such as in cases of  $I(0)$  and  $I(1)$  or even  $I(1)$  series. The TY methodology is built on the vector autoregressive (VAR) value at risk framework ( $K+d_{max}$ ). Here,  $K$  represents the optimum order in the VAR system, while the  $d_{max}$  denotes the maximum order of integration of the series in question. The VAR framework is rendered below for the variables of interest in the current study:

$$\begin{aligned} \text{GDP} = & \beta_1 + \sum_{k=1}^K \beta_{1k} \text{GDPT}_{t-k} + \sum_{d_{max}=i+1}^j \beta_{2j} \text{GDPT}_{t-j} + \\ & \sum_{k=i}^K \alpha_{1k} \text{NGC}_{t-k} + \sum_{d_{max}=k+1}^j \alpha_{2j} \text{NGC}_{t-j} + \\ & \sum_{k=i}^K \delta_{1k} \text{TT}_{t-k} + \sum_{d_{max}=k+i}^j \delta_{2j} \text{TT}_{t-j} + \varepsilon_{1t} \end{aligned} \quad (7)$$

$$\begin{aligned} \text{NGC} = & \alpha_0 + \sum_{k=1}^K \alpha_{1k} \text{NGC}_{t-k} + \sum_{d_{max}=i+1}^j \alpha_{2j} \text{NGC}_{t-j} + \\ & \sum_{k=i}^K \beta_{1k} \text{GDPT}_{t-k} + \sum_{d_{max}=k+1}^j \beta_{2j} \text{NGDPT}_{t-k} + \\ & \sum_{k=i}^K \delta_{1k} \text{TT}_{t-k} + \sum_{d_{max}=k+i}^j \delta_{2j} \text{TT}_{t-j} + \varepsilon_{2t} \end{aligned} \quad (8)$$

$$\begin{aligned} \text{TT} = & \delta_0 + \sum_{k=1}^K \delta_{1k} \text{TT}_{t-k} + \sum_{d_{max}=i+1}^j \delta_{2j} \text{TT}_{t-j} + \\ & \sum_{k=i}^K \alpha_{1k} \text{GDPT}_{t-k} + \sum_{d_{max}=k+1}^j \alpha_{2j} \text{GDPT}_{t-j} + \\ & \sum_{k=i}^K \beta_{1k} \text{NGC}_{t-k} + \sum_{d_{max}=k+i}^j \beta_{2j} \text{NGC}_{t-j} + \varepsilon_{3t} \end{aligned} \quad (9)$$

From Equations 7-9 the variables GDP, NGC, TT are the same as expressed in the data and methodology section. The stochastic terms are expressed as ( $\varepsilon_{1t}$ ,  $\varepsilon_{2t}$ , and  $\varepsilon_{3t}$ ) for the respective equations. The optimal lag,  $K$ , as recommended by the Akaike information criterion (AIC) was employed for our study. To strengthen the causality outcome, we applied the recently developed Fourier approximation TY causality test as advanced by Nazlioglu et al. [10]. This test accounts for a gradual structural shift and smooth shift breaks, which previously established causality tests fail to address. As such, the analyses from this test are reliable and valid for policy direction.

This study also conducted the advanced frequency domain causality test

[9]. This is an improvement upon the Geweke and Hosoya tests [35,36]. The causality test is also known as the spectral Breitung and Candelon (BC) causality test [9]. This is necessary to strengthen the previously conducted conventional causality tests. A dichotomy exists between the frequency domain causality test and the time domain causality test. The frequency domain technique accounts for the degree of certain variations among the variables considered; the domain causality method focuses on the time domain of the series. The frequency domain has merits over the time domain procedure. In short-term series when seasonality patterns and other significant economic episodes exist, the frequency domain accounts for variations. Furthermore, the frequency domain accommodates for non-linearity and causality at diverse cycles, whether low or high frequencies among the series, which other known causality tests fail to address.

This study employs the frequency BC spectral causality test to investigate the causality flow between natural gas consumption (NGC), total trade (TT) and real GDP for the case of Canada. The econometric equations are rendered as  $X_t = [GDP_t, NGC_t, TT_t]'$ , where  $X_t$  is the three-dimensional vector of the endogenous and stationary variables observed at time  $t = 1, \dots, T$ . We assume  $X_t$  has a finite-order VAR representation form as:

$$\Theta(L) X_t = \varepsilon_t \quad (10)$$

For Equation 10,  $\Theta(L)$  is a  $3 \times 3$  lag polynomial of order  $p$  which is presented as  $\Theta(L) = I - \Theta_1 L - \dots - \Theta_p L^p$  with  $L^k X_t = X_{t-k}$ . The residual term,  $\varepsilon_t$ , follows the white noise process with an expectation of zeros and  $E(\varepsilon_t \varepsilon_t') = \Sigma$ , where  $\Sigma$  is positive and symmetric. Following the work of Breitung and Candelon (2006), no deterministic terms are added to Equation 10.

Given that  $\Sigma$  is positive, definite and symmetric, a Cholesky decomposition  $G'G = \Sigma^{-1}$  is present, where  $G$  denotes the lower triangular matrix and the upper triangle matrix is indicated by  $G'$ . In this case,  $nE(n\eta_t \eta_t') = I$  and  $\eta_t = G\varepsilon_t$ . Using this Cholesky decomposition, the moving average (MA) representation of the system is given as:

$$\begin{aligned} X_t &= GDP_t NGC_t TT_t = \Theta(L) \varepsilon_t = \\ \Theta_{11} L \Theta_{12} L \Theta_{21} L \Theta_{22} L \Theta_{31} (L) \Theta_{32} (L) \varepsilon_{1t} \varepsilon_{2t} \varepsilon_{3t} \end{aligned} \quad (11)$$

$$\begin{aligned} X_t &= GDP_t NGC_t TT_t = \Psi(L) \eta_t = \\ \Psi_{11} L \Psi_{12} L \Psi_{21} L \Psi_{22} L \Psi_{31} (L) \Psi_{32} (L) \eta_{1t} \eta_{2t} \eta_{3t} \end{aligned} \quad (12)$$

For Equations 12 and 13,  $\Phi(L) = \Theta(L)^{-1}$  and  $\Psi(L) = \Phi(L)G^{-1}$ . Using this representation, the spectral density of FSt can be expressed as:

$$f_{NGC}(\omega) = 1/2\pi \{ |\Psi_{11}(e^{-i\omega})|^2 + |\Psi_{12}(e^{-i\omega})|^2 \} \quad (13)$$

In Equations 11 and 12 GDP can be described as a sum of two uncorrelated MA processes, which are: the intrinsic component driven by the past realization of GDP, and the component that contains the predictive power of the NGC and TT variables. The predictive power of the NGC and TT variables can be derived at each frequency,  $\omega$ , in relation to the predictive component of the spectrum with the intrinsic component at that frequency. The null hypothesis of no Granger causality is tested among the series [9]. For instance, GDP does not per Granger cause NGC at frequency  $\omega$ , if the predictive factor of the NGC spectrum at frequency  $\omega$  is zero. This informs the causality test of Andrews [35] and Geweke [36] for the x and y variables, as expressed by:

$$M_{x \rightarrow y}(\omega) = \ln [ (2\pi f_y(\omega)) \div (|\Psi_{11}(e^{-i\omega})|^2) ] \quad (14)$$

$$= \ln [ 1 + (|\Psi_{12}(e^{-i\omega})|^2) \div (|\Psi_{11}(e^{-i\omega})|^2) ] \quad (15)$$

Equations 14 and 15 when related to Geweke's measure would equal zero when  $(|\Psi_{12}(e^{-i\omega})|^2) = 0$ . A linear restriction is applied on the VAR using Equation 1, which is expressed as:

$$GDP_t = \alpha_1 GDP_{t-1} + \alpha_p GDP_{t-p} + \beta_1 NGC_{t-1} + \beta_p NGC_{t-p} + \beta_1 TT_{t-1} + \beta_t TT_{t-p} + \varepsilon_t$$

Where the  $\alpha$ s and  $\beta$ s are the coefficients of the lag polynomials.

The null hypothesis  $M_{GDP \rightarrow NGC}(\omega) = 0$  is equivalent to the linear restriction,  $H_0: R(\omega)\beta = 0$ .

Where  $\beta = [\beta_1, \dots, \beta_p]'$  is the vector of the coefficients of GDP, while  $R(\omega)$  is:

$$R(\omega) = [(\cos(\omega) \cos(2\omega) \dots \cos(p\omega))] \div [(\sin(\omega) \sin(2\omega) \dots \sin(p\omega))] \quad (16)$$

The ordinary F statistic for Equation 8 is approximately distributed as F(2, T - 2p) for  $\omega \in (0, \pi)$ , where 2 is the number of restrictions and T is the number of observations used to estimate the VAR model of order p.

## RESULTS AND INTERPRETATIONS

Next we discuss the results of the analysis. Before interpreting the simulation in time series analysis, it is best practice to analyze the summary statistics. This provides insights into the dataset. Table 1 presents the basic summary statistics and data sources. The summary statistics report the measure of central tendencies including the median, maximum and minimum, and reports the measures of dispersion such as the deviation from the mean and standard deviation. According to the data, economic growth exhibits the highest average over the sampled period followed by NGC and TT volume. All series displayed light tail, as none of the variables has a Kurtosis greater than 3. In terms of the symmetry nature among the variables, all were negatively skewed over the sampled period with the exception of TT. The symmetric nature of the variables was also confirmed by the Jarque-Bera probability.

**Table 1. Data and descriptive statistics (in 2010 U.S. dollars).**

<i>Data Source Code</i>	<i>Real GDP WDI GDP</i>	<i>Natural Gas Consumption EIA NGC</i>	<i>Total Trade WDI TT</i>
Mean	37,122	66.86	8.60
Median	36,489.	65.78	8.06
Maximum	51,315	115.75	11.86
Minimum	21,260	21.67	5.81
Std. Dev.	9,000.9	24.28	2.15
Skewness	-0.008	-0.042	0.18
Kurtosis	1.797	1.989	1.28
Jarque-Bera	3.195	2.270	6.66
Probability	0.202	0.321	0.035**

Note: WDI represents word development indicator while EIA denotes U.S. Energy Information Agency. The superscript \*\* denotes  $p < .05$  level of statistical significance.

We next investigate the stationarity properties among the series by using the DF-GLS and Zivot and Andrews (ZA) unit root test, as reported in Table 2. All test statistics of the DF-GLS and ZA unit root test reveal that *natural gas consumption*, *economic growth* and *total trade* are stationary at first difference. In other words, both tests are in harmony and the variables are integrated of order 1, i.e.,  $\sim I(1)$ . The ZA unit root test report a single break date. From Table 2, we observe that the years 1992, 1993, and 2008 were break dates that reflect important economic episodes for Canada, the most notable being the 2008 global financial crisis.

Given the integration order of the variables is of order 1, it is therefore possible to perform cointegration analysis. Thus, we conducted a cointegration



Table 2. Unit Root Tests

		<i>GDP</i>	<i>ΔGDP</i>	<i>NGC</i>	<i>ΔNGC</i>	<i>TT</i>	<i>ΔTT</i>
DF-GLS	CandT		-1.669	-5.396	-2.375	-7.519	-1.572
		MZ <sub>a</sub>	-6.702	-23.588**	-9.887	-25.334**	-4.387
		MZ <sub>t</sub>	-1.694	-3.419**	-2.109	-3.503**	-1.477
Ng-Perron	CandT	MSB	0.252	0.144**	0.213	0.138**	0.336
		MPT	13.685	3.951**	9.715	3.926**	20.738
			-3.069	-6.061**	-3.066	-5.745**	-3.229
ZA	CandT		(2008)	(1993)		(1992)	
			**			**	

Note: CandT denote constant and trend in the DF-GLS and Ng-Perron unit root tests, respectively. Δ denotes the first difference of the time series variables. \*\* and \* denote statistical significance at  $p < 0.05$  and  $p < 0.10$ , respectively. ( ) represent break points.

test that accounts for a single structural break, a shift, plus a smooth gradual shift rather than the conventional cointegration tests. Table 3 presents the cointegration test results for the variables under consideration. In Table 3A, the statistical significance of the test statistic of the Hatemi-J approach to cointegration testing at the  $p < 0.05$  level shows the presence of a long-run equilibrium relationship among the series. This is also confirmed using Gregory and Hansen’s approach to cointegration testing, as reported in Table 3B [33].

Table 3. Cointegration Tests

3A	<i>Hatemi-J cointegration with two unknown breaks</i>		
	<i>ADF</i>	<i>Z<sub>t</sub></i>	<i>Z<sub>a</sub></i>
Test statistic	-6.709**	-6.589**	-38.276
	(0.301, 0.679)	(0.302, 0.698)	(0.302, 0.698)
3B	<i>Gregory-Hansen Test for cointegration with regime shifts</i>		
	<i>ADF</i>	<i>Z<sub>t</sub></i>	<i>Z<sub>a</sub></i>
Test statistic	-6.83**	-6.03**	-34.01
	(1997)	(1997)	(1997)

Notes: Numbers in parentheses in 3A represent break points while \*\* and \* denote statistical significance at  $p < 0.05$  and  $p < 0.10$ , respectively [7:501 for the critical values for the Hatemi-J cointegration tests]. Modified ADF\* and  $Z_t^*$  test statistics reject the null hypothesis of no cointegration at the  $p < 0.05$  level of significance.

Finally, a series of causality tests was conducted to examine the direction of causality and test whether *natural gas consumption*, *total trade* and *economic growth* are useful predictors of one another. The first set of causality tests are time domain and both are in agreement regarding the causal relationship among the variables. According to the results of the TY and gradual shift causality tests, there is a two-way causality between *NGC* and *GDP* as well as between *TT* and *GDP* at  $p < 0.05$  and  $p < 0.10$  significance levels, respectively. These results indicate that *NGC* and *TT* per Granger cause economic growth. By implication, *NGC* and *TT* are useful predictors of economic growth, as an increase and/or

decrease in either significantly impacts Canada's level of economic output for the long run.

**Table 4. Causality tests**

	$NGC \rightarrow GDP$	$TT \rightarrow GDP$	$GDP \rightarrow NGC$	$GDP \rightarrow TT$
TY Causality	$\langle 3.487 \rangle^*$ (0.061)	$\langle 3.318 \rangle^*$ (0.068)	$\langle 12.230 \rangle^{**}$ (0.002)	$\langle 7.068 \rangle^{**}$ (0.034)
Gradual Shift Causality	$[9.651]^{**}$ (0.008)	$[12.801]^{**}$ (0.046)	$[30.706]^{**}$ (0.000)	$[19.864]^{**}$ (0.002)

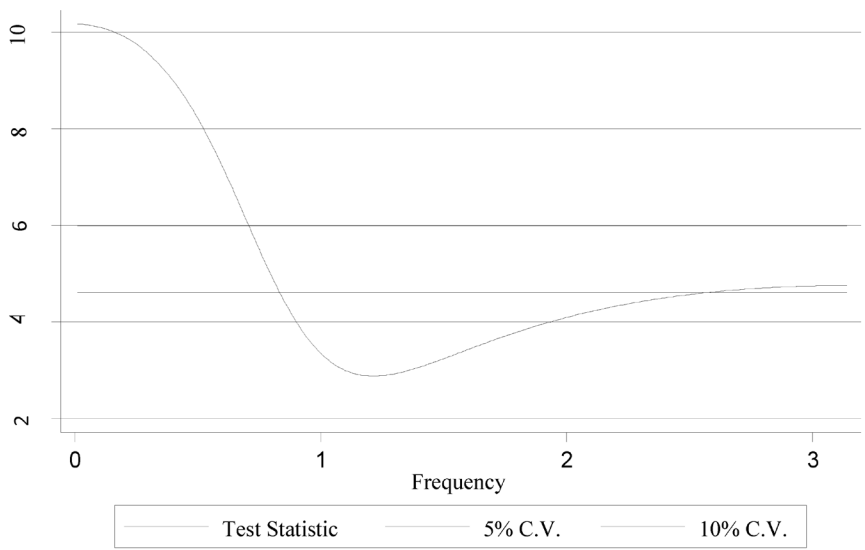
Note: the values within the [ ], ( ), and  $\langle \rangle$  symbols indicate test stat, p-value, and MWALT, respectively. The optimal lag for our causality models is selected using AIC technique.  $\rightarrow$  denotes the direction of causality. \*\* and \* denote statistical significance at the  $p < 0.05$  and  $p < 0.10$ , respectively.

Furthermore, as a sensitivity check, the frequency domain causality test advanced by Breitung and Candelon (BC) was conducted to justify and provide insights into the causality analysis in terms of its merits over conventional time domain causality tests. It offers characterization across the frequencies from the long to the short term while accounting for non-linearity [9]. In other words, frequency domain causality allows us to capture permanent (long term) and temporary (short term) causalities. Figures 1 through 4 present the BC spectral graphical plots for this study. The results of the plots show a strong and persistent long-run bidirectional causality relationship running from *NGC* to real *GDP* (Figure 1) and from real *GDP* to *NGC* (Figure 3). Rejecting the null hypothesis that *NGC* does not per Granger cause economic growth over the sampled period (1965 through 2017) for the frequencies in the intervals between 0 and 1, and vice versa. Based on Figures 2 and 4, we reject the null hypothesis that total trade does not per Granger cause economic growth, and economic growth does not per Granger cause total trade at low frequency levels. This indicates that total trade is a useful predictor of economic growth and vice versa. This outcome is consistent with the time-domain causality test results presented in Table 4. Thus, the results are reliable and consistent for use in policy development.

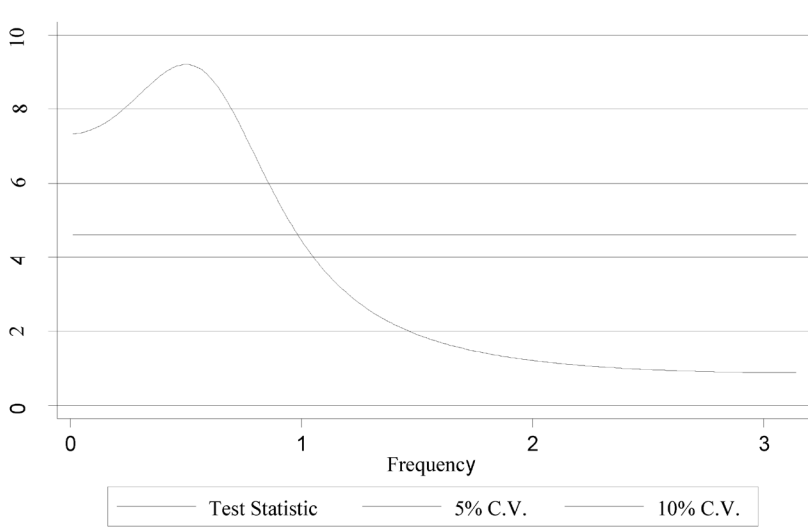
Consequently, these findings offer insights for policymakers responsible for policies that would enhance the consumption of NG and also promote trade. It will be theoretically correct and empirically justified to conclude that Canada's economic growth is driven by in part natural gas trading.

## CONCLUSION AND POLICY DIRECTION

Natural gas is favored over other fossil fuels such as coal and oil since it emits less greenhouse gases per unit of energy when combusted [37]. It is an



**Figure 1. Spectral BC causality from natural gas consumption to real *GDP*.**



**Figure 2. Spectral BC causality from total trade to real *GDP*.**

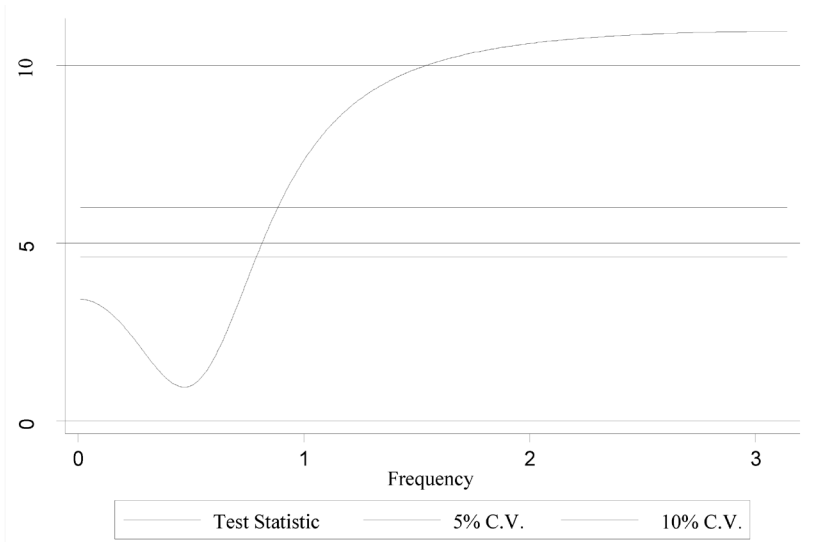


Figure 3. Spectral BC causality from real *GDP* to natural gas consumption.

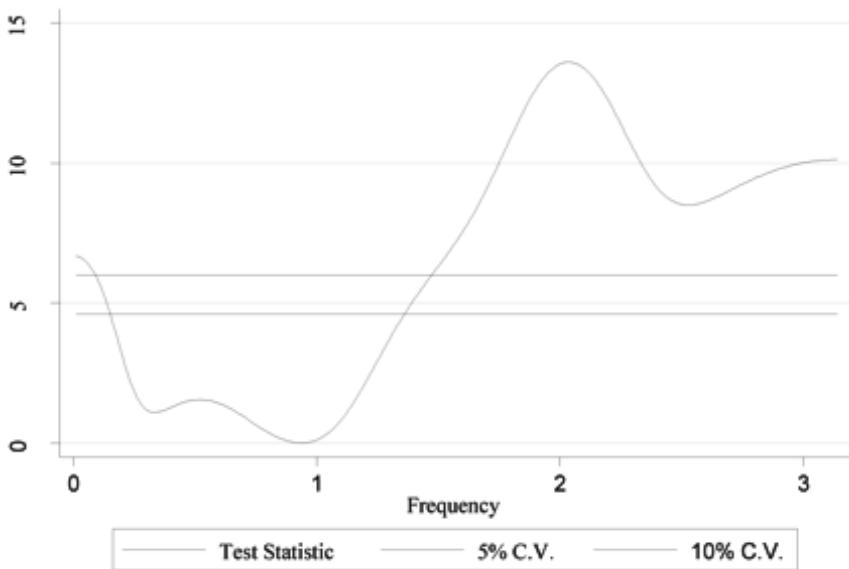


Figure 4. Spectral BC causality from total trade to natural gas consumption.

ideal fuel for export due to its handling and transportation advantages [37]. Canada benefits economically by exporting NG to the U.S. and elsewhere. This study explores the interaction between Canada's NG consumption and economic growth in a multivariate framework by incorporating total trade using annual data from 1965 through 2017. It is distinct from previous studies found in the literature in terms of scope as it includes total trade in the NG and economic growth data. This is considered appropriate given Canada's position as a major NG exporter.

This study makes a valuable contribution by using recently-developed and consistent econometric procedures. First, the ZA unit root test employed is robust and consistent in the presence of a single structural break. Second, for the cointegration analysis, we relied on Hatemi-J's cointegration test that accommodates for possible structural breaks. Finally, this study used both time domain causality tests, the recently-developed gradual shift causality test proposed by Nazlioglu et al. and the frequency domain causality test advanced by Bretung and Candelon as it offers more characterization across different frequencies [8-10]. This makes our findings robust and reliable for policy formulation.

The variables of interest in our study were integrated to the order 1. We investigated the possibility of a long-run equilibrium relationship among the considered variables, as reported by the Hatemi-J cointegration test. The results indicate the existence of an equilibrium relationship, implying that both natural gas consumption and total trade are key drivers of economic output in the Canadian economy. Subsequently, a series of causality tests were conducted to detect the direction of causality among these variables. The causality test in Table 4 for the time domain causality underlines the significant role of NGC, while also accounting for the role of total trade. Similarly, the frequency domain causality tests (see Figures 1 through 4) confirm long-run persistent causalities flowing from both NGC and total trade to economic growth. The combined results of both the time and frequency domain causality tests confirm the robustness of the one-way causality from NGC to economic growth well as the unidirectional causality from total trade to economic growth.

Our findings strongly suggest that it is pertinent for policymakers responsible for energy efficiency and conservation policies to be cautious when formulating policies that could facilitate a cleaner environment by reducing pollutant emissions in Canada. This is important to economies that are prioritizing the reduction of GHG emissions. Lastly, given the reductions in Canadian NG exports to the U.S., coupled with the quest to reduce GHGs to sustain a clean environment for current and future generations, pressures to reduce NG

usage and failures to promote its trade might negatively impact on economic output. Canada must both embrace and curtail its NG consumption to achieve national environmental sustainability objectives. We believe that energy and environmental policies that encourage the use of both renewable and non-renewable energy sources should be pursued in Canada, and also in nations that are natural gas-trade dependent.

Lastly, our study uses recent econometric techniques that are robust to breaks and generate reliable test statistics to support our research objective that was to empirically prove that NG exports predict total trade and economic growth in Canada. Future studies on this or related topics can be conducted for other regions of the world to verify the validity of the natural gas-trade-economic growth proposition.

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