

Optimal Supply Chain of Electrolysis-Based Hydrogen Considering Optimal Power Flow

BY

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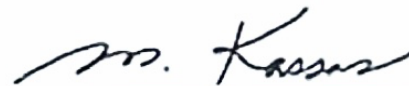
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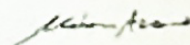
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DEDICATION

I dedicate this thesis to my beloved family and friends

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LIST OF ABBREVIATIONS

SA: Saudi Arabia

GA: Genetic Algorithm

OPF: Optimal Power Flow

NOMENCLATURE

AC	Annual capital charge factor for transportation	y	$S_{g,s}^L$	Minimum storage capacity in the s th storage facility at the g th grid	kg
$UPCF_t$	Unit production cost	\$/kg			
$USCF_s$	Unit storage cost	\$/kg	$S_{g,s}^U$	Maximum storage capacity in the s th storage facility at the g th grid	kg
$S_{g,s}$	Hydrogen stored in the s th facility at grid g	kg/d			
$FCon_{g,g'}$	Fuel consumed transporting from g to g'	kg/d	NS_g	Number of hydrogen storage facilities in the g th grid	--
FCF	Price of the fuel used	\$/kg	$CAPEX$	Capital cost	\$/d
$T_{g,g'}$	Delivery time of product from g to g'	h/d	PCF_t	Electrolyzer capital costs	\$
WCF	Driver's wage factor for transportation	\$/h	SCF_t	Storage facilities capital costs	\$
$D_{g,g'}$	Distance driven to transport product from g to g'	km/d	AC_t	Annual capital charge factor for the t th electrolyzer	y
MCF	Unit cost for transportation per travelled distance	\$/km			
TI	Transportation insurance cost	\$/d	AC_s	Annual capital charge factor for the s th storage facility	y
LR	License and regulation cost transportation	\$/d	OT	Network's annual operating time	d/y
OF	Outstanding finances cost for transportation	\$/d	$NT_{g,g'}$	Number of transportation units from g to g'	--
τ	Total storage period	d	TCF	Cost of establishing transportation unit	\$
CF	Objective cost function	\$/d	P_g	Active power at g th grid bus	MW
Γ^{Elz}	Electrolyzer conversion factor = 360	m ³ /MWh	Q_g	Reactive power at g th grid bus	MVar
η^{Elz}	Efficiency of the electrolyzer unit = 60%	%	$P_{g,max}$	Maximum active power at g th grid bus	MW
$X_{g,g'}$	Binary variable denoting the transfer of product from grid g to g'	--	$P_{g,t}$	Active power at t th electrolyzer in the g th grid	MW

V_g	Voltage magnitude at g^{th} grid bus	Pu	$F_{g,t}$	Hydrogen production in the t^{th} electrolyzer at grid g	kg/d
$V_{g,min}$	Minimum voltage magnitude at g^{th} grid bus	Pu	$F_{g,t}^L$	Minimum production capacity in the t^{th} electrolyzer at the g^{th} grid	kg/d
$V_{g,max}$	Maximum voltage magnitude at g^{th} grid bus	Pu	$F_{g,t}^U$	Maximum production capacity in the t^{th} electrolyzer at the g^{th} grid	kg/d
$Y_{g,g'}$	Admittance magnitude from g to g' grids buses	Pu	NF_g	Number of electrolyzers in the g^{th} grid	--
δ_g	Voltage angle at g^{th} grid bus	Rad	$Q_{g,g'}^L$	Minimum flowrate between grids' pairs	kg/d
P_{TLoss}	Total network power loss	MW/d	$Q_{g,g'}^U$	Maximum flowrate between grids' pairs	kg/d
C_p	Power cost	\$/MWh	$X_{g,g'}$	Binary variable denoting the transfer of product from grid g to g'	--
$Q_{g,min}$	Minimum reactive power at g^{th} grid bus	MVar	S_g	Total inventory in grid g	kg
$Q_{g,max}$	Maximum reactive power at g^{th} grid bus	MVar			
P_{TLoad}	Total active power demand	MW/d			
θ_g	Angle at g^{th} grid bus	Rad			
$\theta_{g,min}$	Minimum angle at g^{th} grid bus	Rad			
$\theta_{g,max}$	Maximum angle at g^{th} grid bus	Rad			
D_g	Hydrogen demand at the g^{th} grid	kg/d			
F_g	Hydrogen production at the g^{th} grid	kg/d			
$Q_{g',g}$	Flowrate from g' to g	kg/d			

THESIS ABSTRACT – ENGLISH

Full Name: Riyadh Mohammad Nasser Al-Aqeeli

Thesis Title: Optimal Supply Chain of Electrolysis-Based Hydrogen
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This thesis focuses on the optimal supply chain of electrolysis-based hydrogen generation plants considering optimal power flow. The thesis covers all the supply-chain aspects; generation plants, storage facilities for emergency supply response, and transportation. In addition, a mathematical model has been presented to simulate the topic goals as well as the deployment objective. The mathematical model takes into account the daily capital cost of production plants and storage facilities, the daily capital cost of transportation network, operating costs associated with the hydrogen production plants and storage facilities, transportation fleet fuel cost, transportation labor cost, miscellaneous hydrogen transportation cost, maintenance cost of the

transportation network, power consumption and related losses which are all subjected to several constrains.

The mathematical model has been implemented on SA for the deployment of the technology. The model showed outstanding planning of supply-chain for hydrogen within the kingdom, and four scenarios have been implemented to verify the mathematical model's reliability. In addition, the intelligent solving approach GA has been utilized to solve the problem and increase the efficiency in approaching the model.

ملخص الرسالة

الاسم الكامل: رياض بن محمد بن ناصر العقيلي

عنوان الرسالة: أمثل سلاطة إمداد لمادة للهيدروجين المصنع عن طريق التحليل الكهربائي مع الأخذ

بعين الاعتبار الطاقة الكهربائية المتدفقة

التخصص: هندسة الكهرباء

تاريخ الدرجة العلمية: مارس ٢٠٢٣

في هذه الرسالة، ينصب التركيز على أمثل سلسلة إمداد لمادة الهيدروجين المصنع عن طريق التحليل الكهربائي مع الأخذ بعين الاعتبار الطاقة الكهربائية المتدفقة. هذه الرسالة تأخذ في عين الاعتبار جميع أوجه سلسلة الإمداد التي تشمل توليد الهيدروجين، تخزين الهيدروجين للغرض الطارئ، نقل الهيدروجين بالإضافة، معادلة رياضية تم تقديمها في هذه الرسالة لمحاكاة أهداف الموضوع وتطبيقه عملياً في أرض الواقع. المعادلة الرياضية تأخذ في عين الاعتبار تكلفة رأس المال اليومية لمعامل إنتاج الهيدروجين وتخزينه، تكلفة رأس المال اليومية لشبكة النقل، تكاليف التشغيل اليومية لمعامل الإنتاج والتخزين، تكلفة الوقود اليومية لشبكة النقل، تكلفة الأيدي العاملة والصيانة اليومية لشبكة النقل، التكلفة المتنوعة لشبكة النقل، والتكلفة اليومية للكهرباء مع الأخذ بعين الاعتبار الطاقة المفقودة من النقل بالإضافة الى ربط هذه الأوجه بقيود معينة.

المعادلة الرياضية تم تطبيقها على المملكة العربية السعودية لغرض إمكانية التطبيق الفعلية في أرض الواقع وقد قدمت نتائج متميزة لتخطيط سلسلة إمداد للهيدروجين في المملكة بالإضافة لتطبيق هذه

المعادلة الرياضية على معاملات إدخال مختلفة لإظهار إمكانية المعادلة المتميزة بالإضافة الى استعمال طريقة الحل الذكية المسماة بالخوارزمية الجينية لحل المعادلة وزيادة كفاءة الحل.

CHAPTER 1

INTRODUCTION

The quantity of carbon releases that exist in our ambiance contributes heavily to global warming, which then contributes to climate change that has a number of detrimental consequences that are considered hazardous to nature, humanity and animal being, and our future, such as the ice caps melting, increasing seawater altitudes, disruption of animals' natural environments, and severe weather incidents. However, businesses can play an important part in the mitigation of these environmental pollution issues and could enhance the situation through the introduction of innovations and new sustainable products as well as best practices [1]. This is a response to the previously mentioned impacts that occur on society in general [2]. Preventing pollution and introducing the concept of recycling and plastic reuse as well as utilization of renewable resources in addition of penalizing for energy efficiency along with

the management of carbon emissions are all necessary part contributing to the environmental management system [3].

The importance of a green economy is widely acknowledged by scientists, authorities, experts, and academics, who also concur that it will be impossible to achieve without the deployment of environmental-friendly technologies [4]. Therefore, this thesis will target the optimal way of CO₂-free hydrogen-generated utilization considering the optimal supply chain as well as optimal power flow.

1.1 HYDROGEN TECHNOLOGY

As it is commonly known, hydrogen substance is the most abundant substance in the universe. In addition, it is found that hydrogen has approximately three times of heat per unit mass as that of gasoline [5][39]. Furthermore, it is a clean as well as renewable energy source. Hence, given the current environmental problems caused by the burning of fossil fuels, hydrogen energy is a practical option for meeting future energy needs. In fact, it is currently a vital part of a number of energy systems [6]. There are many ways to utilize hydrogen, mainly through fuel cells that have a high-power conversion factor [7].

Moreover, it can be produced in multiple ways, which will be discussed in the next chapter.

1.2 HYDROGEN SUPPLY-CHAIN

As stated by Beamon B. in [10], the definition of a supply chain is “a structured manufacturing process wherein raw materials are transformed into finished goods, then delivered to end customers”. In addition, Bridgefield Group in [11] defined a supply chain as “a connected set of resources and processes that starts with the raw materials sourcing and expands through the delivery of finished goods to the end consumer.” Furthermore, in [12], a supply chain was defined by Pienaar W. as “a general description of the process integration involving organizations to transform raw materials into finished goods and to transport them to the end user.”

A supply chain’s links and nodes carry out tasks that increase the value of the commodities being transported via the network and hence its success. Any connection that performs poorly lowers the supply-chain’s overall efficacy [13]. Therefore, in this study, the optimal supply-chain of hydrogen will be presented and carried out in the upcoming chapters.

1.3 OPTIMAL POWER FLOW

The minimizing of transmission costs and the operation of power systems both depend on the optimal power flow (OPF) problem being solved. It is a challenging nonlinear optimization problem target to optimize steady-state power system operation with vast dimensions and strict constraints [14]. The OPF problem's application in power system operations has been forced by computational challenges. Since the electrolysis-based hydrogen generation will be based on grid power supply, then the optimal power flow will also be considered on the model for model comprehension, and this will be elaborated more in the next chapters.

1.4 STATEMENT OF THE PROBLEM

Petroleum products like gasoline, as well as diesel, are the primary raw materials used in the worldwide market's transportation industry [8]. In Saudi Arabia, the demographic increase, relatively low gasoline prices, and rising GDP are the main drivers of the annual increase in oil demand. Policymakers could take into account a number of various techniques to decrease domestic oil utilization, including 1) promotion of and investment in public transportation systems, 2) penalizing for vehicle efficiency, 3) matching the

gasoline price to the international market, and 4) promoting the utilization of alternative fuels for the transportation sector [9].

All of the aforementioned options are suitable, and combining one or two will lead to greater benefits. However, considering hydrogen fuel for the transportation sector is one of the most appropriate options. This alternative fuel has been introduced for two key reasons: 1) being a clean fuel without CO₂ emissions, and 2) it can be produced from multiple energy resources such as biomass, electrolysis-based systems, and fossil-based process integrated with carbon capture and storage (CCS) systems.

However, the system level, including optimal electrolysis-based hydrogen generation, storage, and transportation to meet the hydrogen loads considering optimal grid power flow, is missing in the literature. Therefore, electrolysis-based hydrogen production, transportation, and storage (supply chain), together with the operational capacity and optimal power flow, are considered in this thesis. The capital, operational, and fuel expenses connected with the various design and operations of electrolysis-based hydrogen supply chains are also included. The ideal design and operation for the future of SA at steady-state are established in this work. The issue is how to fulfill future hydrogen

demand while staying within technological, economic, and environmental constraints.

1.5 RESEARCH OBJECTIVES

The main objectives of this research work are but not limit to:

1. Investigating the optimal supply chain of electrolysis-based hydrogen.

Several considerations need to be taken into account for the optimal supply chain of hydrogen, which include distances between possible generation points, maximum transportation capacity, maximum and minimum generation capability, maximum and minimum storage capability, etc..

2. Evaluating optimal power flow during the supply to electrolyzes.

Losses within the power system network can contribute significantly to the total cost of operation. Therefore, considering optimal power in the optimization of the supply-chain problem will support the reduction of the total operation cost.

3. Developing a mathematical model for the optimal supply chain of electrolysis-based hydrogen considering optimal power flow.

A mathematical model is essential in evaluating the effectiveness of the approach. Therefore, an integrated model considering the optimal supply chain of electrolysis-based hydrogen, taking into account optimal power flow, will be presented in this work.

1.6 RESEARCH QUESTIONS

This research work targets answering two important questions for the deployment of electrolysis-based hydrogen infrastructure, which are as follows:

1- What is the optimal way to the utilization of hydrogen fuel?

As stated in the previous section, several perspectives need to be considered during the execution of the hydrogen fuel infrastructure. Therefore, this work will comprehend the overall approach for the optimal supply chain of hydrogen fuel, taking into account the optimal power flow for the hosting grid.

2- What are the cost contributors, and what is the overall cost?

One of the most important considerations from the engineering perspective is the cost. Hence, in this research work, an elaboration on the cost parameters

and how much each parameter contributed in addition to the total expected overall cost will be presented.

1.7 SIGNIFICANCE OF THE STUDY

As stated previously, CO₂ emissions are major issues that affect the environment and well-being in general. Therefore, extensive efforts need to be carried out to mitigate these effects. Hydrogen fuel utilization is considered one of the best alternatives to fossil fuel which will eliminate the CO₂ effects caused by this conventional fueling [8]. Throughout the literature, extensive efforts have been carried out to explore and prove the hydrogen fueling concept, and in the upcoming chapter, a comprehended literature review will be carried out.

This study is the first of its kind and is filling a gap in the literature that will be proven in the next chapter. It provides a comprehensive approach for the supply chain of hydrogen fueling, taking into account optimal power flow for the network with the minimum overall cost of deployment. Furthermore, this work will form the bases for researchers and scholars to provide multiple enhancements to the concept of hydrogen technology.

1.8 SCOPE AND LIMITATIONS

- This research work targets the utilization of hydrogen fuel in Saudi Arabia only. However, the overall approach can be tailored and utilized to any geographical area.
- The daily capital cost of production plants and storage facilities, daily capital cost of transportation network, operating costs associated with the hydrogen production plants and storage facilities, transportation fleet fuel cost, transportation labor cost, miscellaneous hydrogen transportation cost, maintenance cost of the transportation network, and power consumption and related losses are the main contributors to the approach overall cost.
- The powerful Genetic Algorithm (GA) solving technique will be utilized in the solving and optimization of the problem.
- The supply of hydrogen will only consider the transportation fuel demand.

1.9 THESIS ORGANIZATION

This study will begin with a thorough review of the electrolysis-based hydrogen supply chain considering optimal power flow. To confirm that this

work is built on the most recent research or on recommendations for additional research made by scientific studies, recent works will be cited. After that, the methodology will be presented to show how the problem is approached which is in chapter three. Next, the analysis and results will be discussed in a separate chapter. Finally, conclusions, as well as recommendations, will be shared.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

As discussed in the previous chapter, the amount of carbon released into our atmosphere are huge, and a response needs to be taken to mitigate the adverse effects that will be caused by these releases [1]. Transportation is considered one of the biggest contributors to CO₂ emissions caused by fuel consumption, and hydrogen is considered one of the best alternatives [8]. Therefore, it is very important to explore the optimal way of utilizing this technology.

The main goal of this chapter is to explore the latest knowledge shared in the literature and shows how this work is contributing. In addition, the most common hydrogen production, transportation, and storage techniques.

2.2 HYDROGEN PRODUCTION TECHNIQUES

There are many hydrogen production techniques. However, the main techniques utilized for the production are as follows.

2.2.1 STEAM REFORMING

Methane, methanol, ethanol, glycerol, toluene, and acetic acid have all been explored using steam reforming in various ways [15]. Steam-methane reforming (SMR) appears to be the most common method of producing H₂ (which produces roughly 48% of the world's hydrogen) [16]. SMR process is split into two parts: The first needs combining methane and steam to produce mainly H₂ gaseous mixture containing approximately 10% CO₂ and 12% CO. This procedure takes place at roughly 800°C. The water gas shift reaction (WGSR) is the following step, which involves mixing CO with water to produce H₂ gas and CO₂ [6]. On a volume basis, H₂ generation from methane is 2.4:1, presuming a 76 percent SMR efficiency with a CO shift [17]. In addition, one of the most challenging concerns in the SMR process is carbon dioxide capture and storage (CCS), and research and development in this area are still in their early stages.

2.2.2 BIOMASS GASIFICATION

The process of biomass gasification begins with the heating of biomass to produce syngas, mostly made up of H_2 , CO, CO_2 , and water. After the gas has been purified, steam is added, leading the WGSR to convert CO energy into H_2 . The H_2 is separated from the CO_2 via a process known as pressure swing absorption (PSA). This technique is similar to coal gasification in many aspects. Biomass offers a number of advantages over coal as a source of hydrogen, one of which is its lower cost [18]. The most significant concern for the future of biomass gasification is the cost and availability of feedstock [19].

2.2.3 PEM ELECTROLYSIS

In PEM water electrolysis which is the main concern in this thesis, water is electrochemically split into H_2 and oxygen gases at the anode and cathode, respectively (this approach is called green hydrogen production) [20]. PEM electrolysis provides a range of benefits, including a tiny imprint, rapid reaction, the potential to function at lower temperatures (20–80 °C), and the ability to create ultrapure H_2 and by-product oxygen. PEM fuel cells (PEMFCs) are a highly efficient and environmentally friendly power generation technology that may be used in both stationary and portable

applications [21]. However, one of the main challenges faced in this area is the relatively high cost of PEM electrolyzers. Each of the techniques mentioned above has its own set of advantages and disadvantages, as shown in Table 1.

Table 2.1: Comparison for H₂ generation techniques [15]-[21]

Process	Advantages	Drawbacks	Efficiency (%)	Cost (\$/kg)
Steam Reforming	Well-established technology, Produces 99.9% pure H ₂ .	Consumes high energy, High operating cost.	74-85	0.46-0.59
Gasification	High efficiency, environmentally friendly and economically feasible.	Reactor cost is quite high	30-40	1.12-1.31
Electrolysis	Completely clean process O ₂ as a by-product, Zero emission.	Require a high budget for manufacturing and has diminished efficacy relative to hydrocarbon reforming.	60-80	2.30-3.29

2.3 HYDROGEN STORAGE TECHNIQUES

With existing technology, storing, or transporting H₂ on a wide scale is a major difficulty [22]. H₂ has an excellent energy density by weight but a median energy density by volume when compared to hydrocarbons. For instance, liquid hydrogen has 120 MJ/kg and 8 MJ/L, while diesel has 45.5 MJ/kg and

38.6 MJ/L [23]. The storage capacity of such H₂ storage devices must be large in both gravimetric and volumetric aspects. Good H₂ storage materials are lightweight, low-cost, have efficient adsorption-desorption kinetics, and are recyclable. H₂ fuel may be stored in a variety of ways. A comparison in terms of temperature and pressure required as well as the corresponding wt %, MJ/L, and cost for the different ways, is presented in Table 2 [17][24][38].

Table 2.2: H₂ storage techniques

Method	T (K)	P (bar)	Gravimetric Energy Density (wt %)	Volumetric Energy Density (MJ/L)	Cost (\$/Kg)
Compressed	293	700	5.7	4.9	0.24
Liquid	20	0	7.5	8	0.63
Metal Hydride	260-425	20	7.6	13.2	1.33
Metal Organic Framework (MOF)	78	20-100	4.5	7.2	1.5-2

2.4 HYDROGEN TRANSPORTATION TECHNIQUES

Several techniques are deployed for hydrogen transportation, and the main techniques are listed below.

2.4.1 COMPRESSED GAS TRANSPORTATION

Compressed gas can be transported through pipelines, tube trailers, and high-pressure cylinders. H₂ should be compressed to very high pressure before being transported as a gas to optimize the tank capacity [22]. High-pressure gas cylinders, for example, have a pressure rating of 40 MPa and can contain about 1.8 kg of H₂ while being difficult to handle and carry. Tube trailers, which are made up of many steel cylinders fastened to a safety framework, may hold 63-460 kg of H₂ and operate at 20-60 MPa, depending on the number of tubes [25].

2.4.2 LIQUID HYDROGEN TRANSPORTATION

H₂ is delivered in highly insulated double-walled containers to prevent it from boiling off. Some tankers use liquid nitrogen heat shields to cool the external wall of the liquid H₂ vessel, significantly reducing heat transfer. Tank trucks can handle 360-4,300 kg of liquid H₂, whereas rail trains can transfer 2,300-9,100 kg. Truck and rail car boil-off rates range from 0.3 to 0.6 percent per day. The use of barges or seagoing vessels to deliver H₂ across long distances has been proposed [25].

2.4.3 METAL HYBRID TRANSPORTATION

Metal hydrides can be used for transportation by absorbing H₂ with a metal hydride and then loading the full container onto a rail or truck for delivery to the customer's location, where it can be swapped for an empty hydride container or used as a regular tanker [24]. Figure 2.1 compares the cost of transporting H₂ over 200 kilometers.

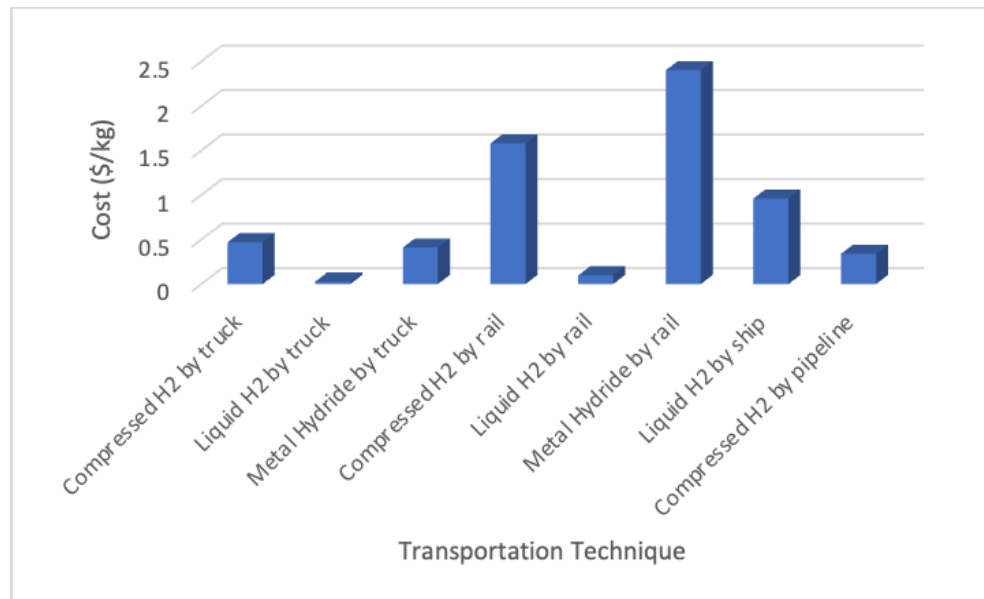


Figure 2.1: Costs of H₂ transportation [25].

2.5 LATEST RESEARCH

For decades, the energy topic has included discussion of hydrogen's possibility as a future fuel. The utilization of hydrogen in future electricity supply chains

for the transportation system, decentralized heat and power production, as well as for electricity storage has been the focus of numerous research initiatives directed by academics and engineers. In order to advance the present hydrogen system and bring it to market, several authorities, including those of the US, the EU, Japan, as well as others, have committed billions of dollars. Automobile and energy entities are focusing and spending huge budgets on building demonstration fleets as well as fueling centers. The feasibility and difficulties of transitioning from an unsustainable carbon-based economy to a sustainable hydrogen economy are also being studied by policymakers. Instead of concentrating on the systems perspective to design and operate such an infrastructure, the majority of these hydrogen activities' demonstration projects and initiatives focus on one specific aspect of the hydrogen supply chain, such as technologies for hydrogen generation, storage, or distribution.

US governmental pressures, notably those in California to improve air quality, were a major factor in the pioneering works in hydrogen technology. The Southern Californian case study to establish a hydrogen vehicle refueling infrastructure is one prominent example. Ogden looked at a few short-term options for manufacturing and transporting hydrogen as a result [26]. The suggested energy supply systems combine commercially existing hydrogen

generation, storage, and distribution technologies with certain still-in-development technologies. Long-term research on different centralized hydrogen generation techniques was done by Ogden in [26] as well, including the gasification of biomass, coal, or municipal solid waste, as well as electrolysis using nuclear, solar, or wind energy. The feasibility of coupling thermochemical hydrogen generation systems with CO₂ separation and sequestration technologies has also been discussed.

In recent years, the UK has also paid more and more attention to the establishment of a hydrogen supply chain. Guy in [27] studied the deployment of a hydrogen transport network in London and the Southeast. From both an economic and environmental standpoint, the difficulties in developing such an infrastructure during the market development period were also covered. Despite a number of technical obstacles that will be removed in the near future with the help of technological developments, he came to the conclusion that the establishment of a hydrogen network is both viable and economically appealing. In addition, the possibility of creating an initial hydrogen infrastructure for refueling hydrogen buses in London, as well as whether this infrastructure could offer a sufficient and adequate platform for private automobiles, were investigated by the authors of [28]. In their study, they

analyzed the technical challenges of setting up a hydrogen facility and provided a framework for simulating a hydrogen infrastructure. The proposed infrastructure was limited to building various scales of on-site hydrogen generation technologies, such as the electrolysis of water and steam methane reforming, and evaluating the operational choices made by such facilities to meet bus demand. However, it might be claimed that the model does not take into account the infrastructure's economics, i.e., crucial for selecting the best arrangement of the hydrogen supply chain.

Mathematical models that encompass and describe every element of the hydrogen supply chain in a unified model have not yet been developed. The combination of production planning with reactive scheduling for the optimization of a hydrogen supply network was studied by the authors in [29]. The network they describe in their article comprises 20 clients, four connected pipelines, and five hydrogen-generating facilities. For both the planning and scheduling levels, they proposed a method for solving multi-period mixed-integer nonlinear programming models. They asserted that their study offers a novel integration strategy that has never been considered previously. However, rather than examining the design elements of the network model itself with the operation, their work focuses on the operational level of an

existing, limited hydrogen supply chain. In [30], the authors presented a model for hydrogen generation and storage, including feasibility analysis. However, optimal power flow has not been considered. Authors in [31] proposed optimal green hydrogen storage facilities capacity sizing based on the renewable potential within the utilization region. However, they did not consider importing hydrogen from neighboring regions for optimal storage facilities capital costs in addition to not considering distribution and power flow. In [32], the authors proposed an optimal investment model for electrolyzes and storage facilities in the hydrogen supply chain. However, the overall hydrogen supply chain (production, storage, distribution, and power supply) has not been investigated. In addition, the authors of [33] proposed a model for optimal green hydrogen generation plants and storage facilities operation. However, comprehending all the components in the system as well as considering them on a large-scale network have not been approached. Furthermore, in [8], the authors investigated the optimal design and operation of future hydrogen technology infrastructure considering generation, transportation, and distribution. However, optimal power flow has not been considered, which can contribute in such a manner to the operation and overall cost.

The system level, including optimal generation, storage, and transportation to meet the hydrogen loads considering optimal power flow is missing in the literature. Therefore, electrolysis-based hydrogen production, transportation, storage, and optimal power network flow, together with the operational levels, are considered in this thesis. The capital, operational, and fuel expenses connected with the various design and operations of hydrogen supply-chain components are also included. The ideal design and operation for the future of SA at steady-state are established in this study. Again, the issue is how to fulfill future hydrogen demand while staying within technological, economic, and environmental constraints.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

In this chapter, the mathematical model for the optimal operation of an electrolysis-based hydrogen supply chain considering optimal power flow will be introduced. In addition, the method incorporated to calculate the expected future hydrogen demand will be elaborated. Furthermore, constraints, as well as equations definitions that constitute the mathematical model, will be discussed. Moreover, the genetic algorithm (GA) intelligent solving approach that will be utilized in solving the model will be presented.

3.2 HYDROGEN DEMAND

The total hydrogen demand in this paper is considered only for the transportation sector. Therefore, the total hydrogen demand of a given geographical area is estimated as a function of the number of taxis, personal cars, and public buses using hydrogen as fuel, their average travelled distance, and fuel economy. Accordingly, the total future hydrogen consumption of a country is calculated by projecting the number of taxis, personal cars, and public buses required in each region (grid) (based on expected population growth), the expected average distances traveled, and expected fuel economy and then converting this demand into hydrogen demand by considering 12 kWh/kg for petrol and diesel and 33.3 kWh/kg for hydrogen [23]. The model considers that each geographic area (grid) has its own deterministic demand. The hydrogen demand must be met by local production and/or imports from neighboring grids.

3.3 MATHEMATICAL MODEL CONSTRAINTS

3.3.1 HYDROGEN DEMAND

The total hydrogen demand of grid g must be lower than or equal to the total grid production in addition to the imported hydrogen from g' to g

$$D_g \leq F_g + Q_{g',g}, \quad \forall g \quad (1)$$

3.3.2 TOTAL HYDROGEN PRODUCTION

The total hydrogen production at a given grid must equal the total hydrogen production of all the generation plants at that grid

$$F_g = \sum_t F_{g,t}, \quad \forall t, g \quad (2)$$

3.3.3 TOTAL HYDROGEN STORAGE

The total hydrogen storage at a given grid must equal the total hydrogen storage of all the storage facilities at that grid

$$S_g = \sum_t S_{g,t}, \quad \forall t, g \quad (3)$$

3.3.4 TOTAL POWER DEMAND

The total power demand to operate the system must equal the total power consumed for all the electrolyzers within the hydrogen infrastructure

$$P_{TLoad} = \sum_g \sum_t P_{g,t}, \quad \forall t, g \quad (4)$$

3.3.5 HYDROGEN PRODUCTION LIMITS

The total hydrogen production at a given grid must meet the lower as well as the upper total hydrogen production capacity of that grid

$$F_{g,t}^L N F_g \leq F_g \leq F_{g,t}^U N F_g, \quad \forall t, g \quad (5)$$

3.3.6 HYDROGEN TRANSPORTATION LIMITS

The total hydrogen transported from grid g' to g must meet the transportation capability of that path

$$Q_{g,g'}^L X_{g,g'} \leq Q_{g,g'} \leq Q_{g,g'}^U X_{g,g'}, \quad \forall g, g'; g \neq g' \quad (6)$$

3.3.7 HYDROGEN TRANSPORTATION DIRECTION

Hydrogen transportation must occur only in one direction to accommodate for cost saving

$$X_{g,g'} + X_{g',g} \leq 1, \quad \forall g, g'; g \neq g' \quad (7)$$

3.3.8 HYDROGEN STORAGE LIMITS

The total hydrogen stored at a given grid must meet the lower as well as the upper total hydrogen storage capacity of that grid

$$S_{g,s}^L N S_g \leq S_g \leq S_{g,s}^U N S_g, \quad \forall s, g \quad (8)$$

3.3.9 HYDROGEN PRODCUTION LIMITS OF A GIVEN GENERATION PLANT

The total hydrogen production of a given plant must meet the lower as well as the upper production capacity

$$F_{g,t}^L \leq F_{g,t} \leq F_{g,t}^U, \quad \forall t, g \quad (9)$$

3.3.10 HYDROGEN STORAGE LIMITS OF A GIVEN STORAGE FACILITY

The total hydrogen storage of a given facility must meet the lower as well as the upper storage capacity

$$S_{g,s}^L \leq S_{g,s} \leq S_{g,s}^U, \quad \forall s, g \quad (10)$$

3.3.11 ELECTROLYSIS-BASED GENERATION

The hydrogen generated by an electrolyzer must equal the supplied power multiplied by the electrolyzer conversion factor as well as the electrolyzer efficiency

$$F_{g,t} = P_{g,t} \Gamma^{Elz} \eta^{Elz}, \quad \forall t, g \quad (11)$$

3.3.12 POWER SYSTEM

The power system network must adhere to the power system network constraints, including active and reactive powers as well as voltage and angles at each bus as formulated below

$$0 \leq P_g \leq P_{g,max}, \quad \forall g \quad (12)$$

$$Q_{g,min} \leq Q_g \leq Q_{g,max}, \quad \forall g \quad (13)$$

$$\theta_{g,min} \leq \theta_g \leq \theta_{g,max}, \quad \forall g \quad (14)$$

$$V_{g,min} \leq V_g \leq V_{g,max}, \quad \forall g \quad (15)$$

$$P_g = V_g \sum_{g'} (V_{g'} Y_{g,g'} \times \cos(\delta_g - \delta_{g'} - \theta_{g,g'})), \quad \forall t, g \quad (16)$$

$$Q_g = V_g \sum_{g'} (V_{g'} Y_{g,g'} \times \sin(\delta_g - \delta_{g'} - \theta_{g,g'})), \quad \forall t, g \quad (17)$$

3.4 MATHEMATICAL MODEL TERMS

3.4.1 CAPITAL COSTS FOR ELECTROLYSIS-BASED HYDROGEN GENERATION PLANTS AND STORAGE FACILITIES

The first term considered in the mathematical model is related to the capital costs for the establishment of the electrolysis-based hydrogen generation plants as well as storage facilities, as depicted in the below equation

$$CAPEX_{Generation \& Storage} = \sum_g \left(\sum_t \frac{NF_g PCF_t}{AC_t OT} + \sum_s \frac{NS_g SCF_s}{AC_s OT} \right) \quad (18)$$

3.4.2 CAPITAL COST FOR TRANSPORTATION

The second term considered in the mathematical model is related to transportation which represents the capital cost for creating the transportation fleet needed to perform the transportation from grid g to g'

$$CAPEX_{Transportatin} = \sum_{g,g'} \frac{NT_{g,g'} TCF}{AC OT} \quad (19)$$

3.4.3 OPERATION COSTS FOR ELECTROLYSIS-BASED HYDROGEN GENERATION PLANTS AND STORAGE FACILITIES

The operating costs related to the hydrogen generation plants as well as storage facilities are also considered in the mathematical model and depicted in the below formula

$$OPER_{Generation \& Storage} = \sum_g (\sum_t F_{g,t} UPCF_t + \sum_s S_{g,s} USCF_s) \quad (20)$$

3.4.4 FUEL COST FOR TRANSPORTATION NETWORK

The fuel cost that will be encountered during the transportation of hydrogen from grid g to g' is also considered in the mathematical model and represented in the below equation

$$Fuel\ Cost = \sum_{g,g'} FCon_{g,g'} FCF \quad (21)$$

3.4.5 LABOR COSTS FOR TRANSPORTATION NETWORK

The cost that will be faced due to labor transportation handling job to transport hydrogen from grid g to g' is also part of the mathematical model and depicted in the below formula

$$Labor\ Cost = \sum_{g,g'} T_{g,g'} WCF \quad (22)$$

3.4.6 MAINTENANCE COSTS FOR TRANSPORTATION NETWORK

The costs to maintain the transportation network and to ensure operation safety during hydrogen transportation from grid g to g' are also part of the mathematical model

$$Maintenance\ Cost = \sum_{g,g'} D_{g,g'} MCF \quad (23)$$

3.4.7 MISCELLANEOUS COST FOR TRANSPORTATION NETWORK

The miscellaneous cost related to the transportation network are part of the mathematical model to ensure model comprehension and it is depicted in the below equation

$$\text{Miscellaneous Cost} = \sum_{g,g'} NT_{g,g'}(TI + LR + OF) \quad (24)$$

3.4.8 COST FOR POWER CONSUMPTION AND TOTAL POWER LOSSES

The cost for the power consumed for hydrogen generation by electrolyzers as well as the power losses encountered for power transmission are all part of the mathematical model as formulated in the below equation

$$\text{Power Cost} = (P_{\text{TLoad}} + P_{\text{TLoss}})C_p \quad (25)$$

3.4.9 OBJECTIVE COST FUNCTION

The objective cost function targeted in our optimization model is the summation of all the previously discussed cost terms subject to the previously discussed constraints and is presented in the below minimization mathematical model

$$\begin{aligned}
OCF = \min \sum_g \left(\sum_t \frac{NF_g PCF_t}{AC_t OT} + \sum_s \frac{NS_g SCF_s}{AC_s OT} \right) &+ \sum_{g,g'} \frac{NT_{g,g'} TCF}{AC OT} \\
&+ \sum_g \left(\sum_t F_{g,t} UPCF_t + \sum_s S_{g,s} USCF_s \right) + \sum_{g,g'} FCon_{g,g'} FCF \\
&+ \sum_{g,g'} T_{g,g'} WCF + \sum_{g,g'} D_{g,g'} MCF \\
&+ \sum_{g,g'} NT_{g,g'} (TI + LR + OF) + (P_{TLoad} + P_{TLoss}) C_p \quad (26)
\end{aligned}$$

3.5 GENETIC ALGORITHM

Genetic algorithm (GA) is considered a population-based optimization technique. The main inspirations of GAs are natural selection as well as the adaptation capacity of species by the utilization of mutation. GAs are commonly used in many areas, including search, optimization, and control [34]. Many intelligent search methods have shown high performance. However, GA is considered one of the well-known robust search methods. They have the ability to perform the search for the global optimum and therefore, they can avoid trapping in a local minimum [35]. Hence, this algorithm will be utilized to find the optimal operation for the electrolysis-based hydrogen generation plants considering optimal power flow. The procedure for implementing GA is as stated below with σ_{past} and σ^*

corresponds to the past and current objective function values, respectively.
[36].

Table 3.1: Genetic algorithm steps

GENETIC ALGORITHM	
1:	Initiation: error tolerance $\varepsilon > 0$; σ_{past} is a big number. Initialize a large population of sampled points θ_s ; the optimizers are $(NP_{p,g}, NS_{s,g})$.”
2:	Evaluate the points in the objective function (1).
3:	If $(\sigma_{\text{past}} - \sigma^*)/\sigma^* < \varepsilon$ or maximum number of iterations reached, report solution θ^* and terminate.
4:	Form a new generation of population by selecting the fittest individuals within the current generation.
5:	Perform crossover and mutation using the techniques stated in [15]
6:	Implement elitism by selecting the best individuals within the current generation to survive to the next generation. Form the new population then go to step 2
7:	

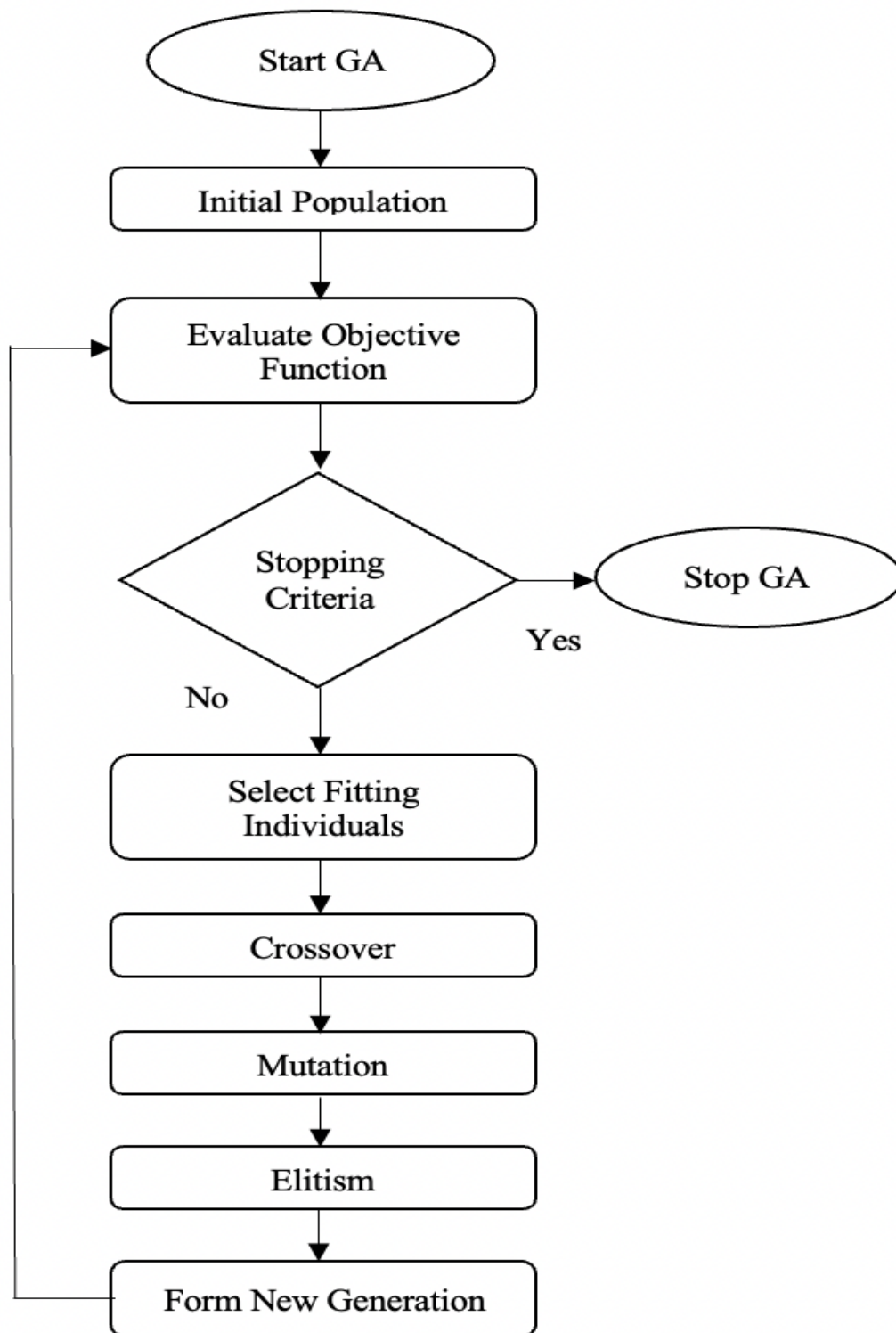


Figure 3.1: Genetic algorithm flowchart.

CHAPTER 4

ANALYSIS AND RESULTS

4.1 INTRODUCTION

In this chapter, analysis, results, and proof for the effectiveness of the model will be presented. Saudi Arabia will be considered as a case study with four different scenarios. It will be divided into 13 regions (grids), and the model will find the optimal regions for the placement of electrolysis-based hydrogen gas generation plants as well as storage facilities in addition to the regions where hydrogen shall be transported instead of local production for optimal supply chain and cost saving.

The model will also provide the number of transportation units (trucks) needed to transport the hydrogen from one grid to another with their required capacities. In addition, it will present all the cost contributors discussed

previously after the optimization with a comparison. The model is solved using the GA in Matlab.

4.2 CASE STUDY

As discussed previously, Saudi Arabia will be divided into 13 regions as illustrated in Fig.4.1 (Northern, Eastern, Riyadh, Jof, Hail, Qassim, Najran, Asir, Jazan, Baha, Makkah, Tabuk, and Madinah) and will be considered under this study. However, the model can be utilized under any geographical area. In addition, four scenarios will be carried out to verify the effectiveness of the model; base scenario that is based on the expected hydrogen demand in 2030 and three modified scenarios of the base scenario which will be elaborated more in the upcoming sections.

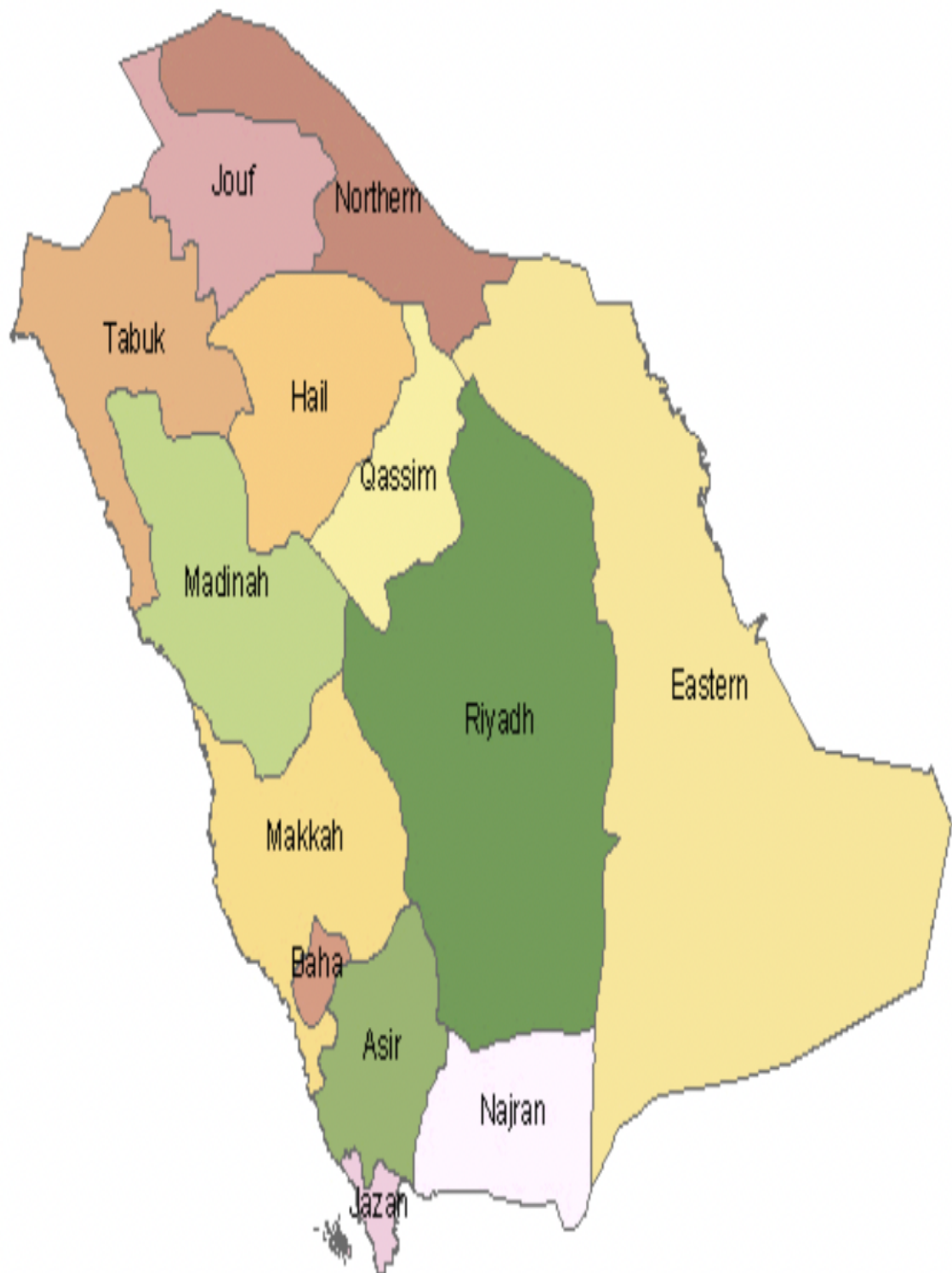


Figure 4.1: Saudi Arabia regions (Grids)

4.2.1 The IEEE-14 BUS SYSTEM

The IEEE-14 bus system has been utilized in this case study and has been scaled down to fit Saudi Arabia as a whole and the average load per year has been considered for the purpose of simplicity and not complicating the idea goal. The system has been scaled down as follows and Fig.4.2 depicts the load of each bus

$$\text{KSA Generation Capacity by 2030} = 64 * 1.1 = 70.4 \text{ GW} \quad (27)$$

$$\text{IEEE-14 Bus System Generation Capacity} = 290 \text{ MW} \quad (28)$$

$$\text{Total H}_2 \text{ Demand} = 51,835 \text{ kg/d} = 2,160 \text{ kg/h} \quad (29)$$

$$\text{H}_2 \text{ Demand Capacity Required by 2030} = \frac{F}{\Gamma_{Elz} \eta_{Elz}} = \frac{\left(2,160 \frac{\text{kg}}{\text{h}}\right) * \left(12.20 \frac{\text{m}^3}{\text{kg}}\right)}{\left(360 \text{ m}^3/\text{MWh}\right) * 0.6} = 122 \text{ MW} \quad (30)$$

Hence, H₂ % demand capacity required from KSA generation capacity =

$$\frac{0.122}{70.4} = 0.17\% \quad (31)$$

Therefore, the scaled-down KSA generation capacity to meet the IEEE-14 bus system constraints is 290 MW with 0.17% for hydrogen generation which equals to 0.5 MW

$$C_1(P_{g1})=[0.005 P_{g1}^2+ 2.45 P_{g1} + 105] \text{ \$/hr} \quad (32)$$

$$C_2(P_{g2})=[0.005 P_{g2}^2+ 3.51 P_{g2} + 44.1] \text{ \$/hr} \quad (33)$$

$$C_3(P_{g3})=[0.005 P_{g3}^2+ 3.89 P_{g3} + 40.6] \text{ \$/hr} \quad (34)$$

$$10 \leq P_{g1} \leq 160 \text{ MW}; 20 \leq P_{g2} \leq 80 \text{ MW}; 20 \leq P_{g3} \leq 50 \text{ MW}; 0 \leq Q_{g1} \leq 10$$

$$\text{MVAR}; 0 \leq Q_{g2} \leq 50 \text{ MVAR}; 0 \leq Q_{g3} \leq 40 \text{ MVAR}; -6.00 \leq Q_{C6} \leq 30$$

$$\text{MVAR}; -6.00 \leq Q_{C8} \leq 30 \text{ MVAR} \quad (35)$$

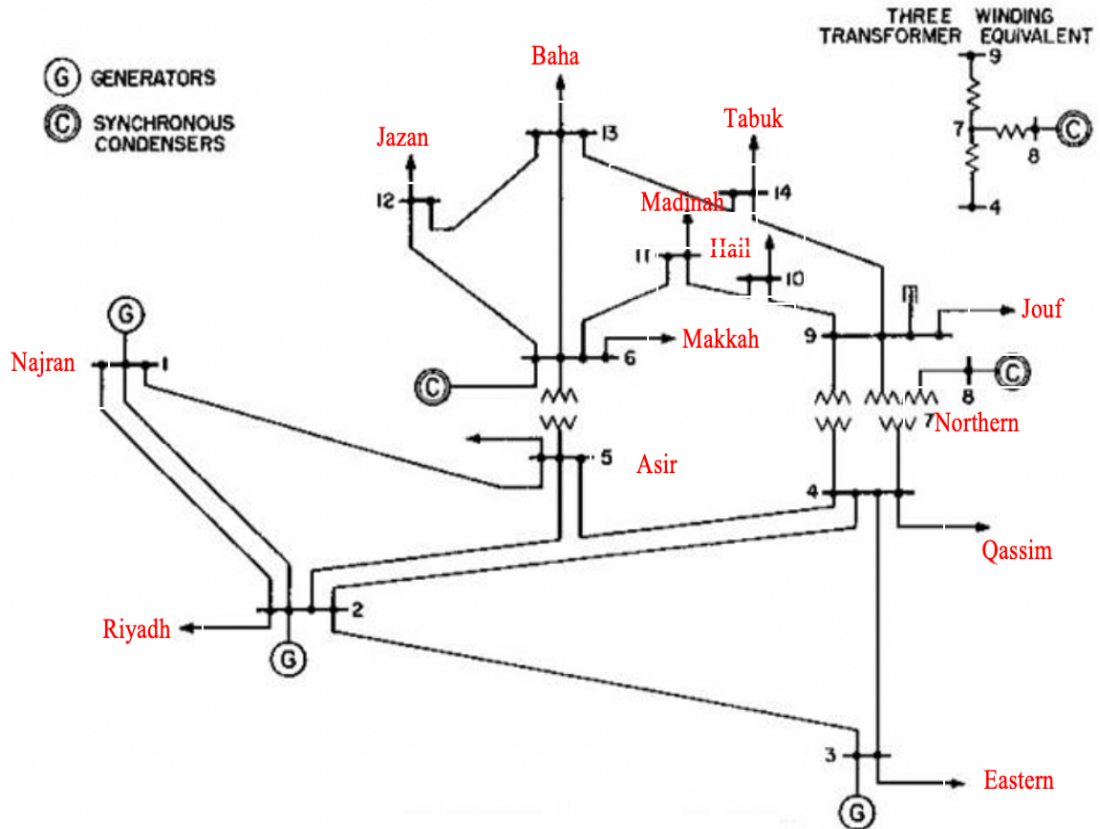


Figure 4.2: The IEEE-14 bus system

4.2.2 BASE SCENARIO

In this base scenario, the hydrogen demand per region (grid) has been calculated based on the methodology discussed previously and is tabulated in Table 4.1.

After the simulation of the model using Matlab with the help of the intelligent solving approach genetic algorithm in addition to the input parameters listed in Appendix I and the utilized IEEE-14 bus system, the following conclusions have been obtained for optimal electrolysis-based hydrogen generation plants supply chain considering optimal power flow

- 1- Riyadh, Eastern, and Makkah will be the only generation regions and the main suppliers to other regions.
- 2- Riyadh will generate 22,121 kg/d of hydrogen in which 17,932 kg/d will be for local supply and 1,724 kg/d for Qassim in addition to 1,597 kg/d for Hail.
- 3- Eastern will be generating 9,031 kg/d in which 8,397 kg/d for local demand and 664 kg/d for Northern.
- 4- Makkah will be generating 20,695 kg/d in which 11,809 kg/d for local supply and remaining for remained regions.

- 5- Each region will contain a storage facility that accommodate the required demand each day for backup and emergency purposes.
- 6- Tables 4.2-4.5 present the mathematical model outcomes and Fig.4.4 depict the supply-chain optimality.

Table 4.1: Expected demand per region in 2030 (Base Scenario)

Region	Demand (kg/d)	Region	Demand (kg/d)
Riyadh	17932	Najran	1282
Eastern	8367	Jazan	2738
Northern	664	Asir	615
Jouf	880	Baha	833
Hail	1597	Makkah	11809
Qassim	1724	Madinah	2051
Tabuk	1355		

Table 4.2: Supply-chain cost (Base Scenario)

Term	Cost (\$/d)
CAPEX _{Generation & Storage}	669,011.67
CAPEX _{Transportation}	8,800.00
OPER _{Generation & Storage}	1,476,260.80
Fuel Cost	2,258.80
Labor Cost	2,276.95
Maintenance Cost	280.24
Miscellaneous Cost	102.76
Total Supply-Chain Cost	2,158,991.22

Term	Cost (\$/d)
Power Cost (Consumption + Losses)	12,111.98
Total Cost	2,171,103.20

Table 4.3: Power flow results (Base Scenario)

Term	Power (MW/d)
G1 Scaled Down Generation	159.99
G2 Scaled Down Generation	80.00
G3 Scaled Down Generation	48.50
G1 Actual Generation	38,838.85
G2 Actual Generation	19,420.69
G3 Actual Generation	11,773.03
Transmission Scaled Down Losses	7.51
Transmission Actual Losses	1,822.25
Hydrogen Power Demand	122.00
Transmission Losses Caused by Hydrogen Supply	3.10

Table 4.4: Power flow summary (Base Scenario)

Bus	Pg (MW)	Qg (MW)	Pd (MW)	Qd (MW)	Voltage (p.u.)	Angle (rad)
1	38,838.85	8,483.60	2,196.38	0	1.05	0
2	19,420.69	4,160.90	14,308.34	3,083.03	1.02	-0.04758405
3	11,773.30	2,690.65	10,998.53	4,636.69	1	-0.08552650
4	0	0	4,389.87	-946.76	0.98	-0.12659168
5	0	0	1,098.25	388.41	0.98	-0.11521017
6	0	1,389.24	8,833.02	1,820.69	1	-0.28066808
7	0	0	0	0	0.99908	-0.23420532
8	0	1,606.90	4,950.71	0	1.01	-0.26981289
9	0	0	4,950.23	4,029.79	0.99398	-0.26866468
10	0	0	3,297.76	1,408.00	0.98297	-0.28665202
11	0	0	5,505.79	436.97	0.97892	-0.30557024
12	0	0	2,192.95	388.41	0.98294	-0.29648434
13	0	0	1,097.74	1,408.00	0.98378	-0.29026575
14	0	0	4,390.74	1,213.79	0.96778	-0.30298894

Table 4.5: Supply-chain summary (Base Scenario)

Term	Value
NF_{Total}	54 units
NS_{Total}	13 facilities
NT_{Total}	33 units
$FCon_{Total}$	6844.86 kg/d
T_{Total}	87.575 hrs. payment/d
D_{Total}	7006 km/d

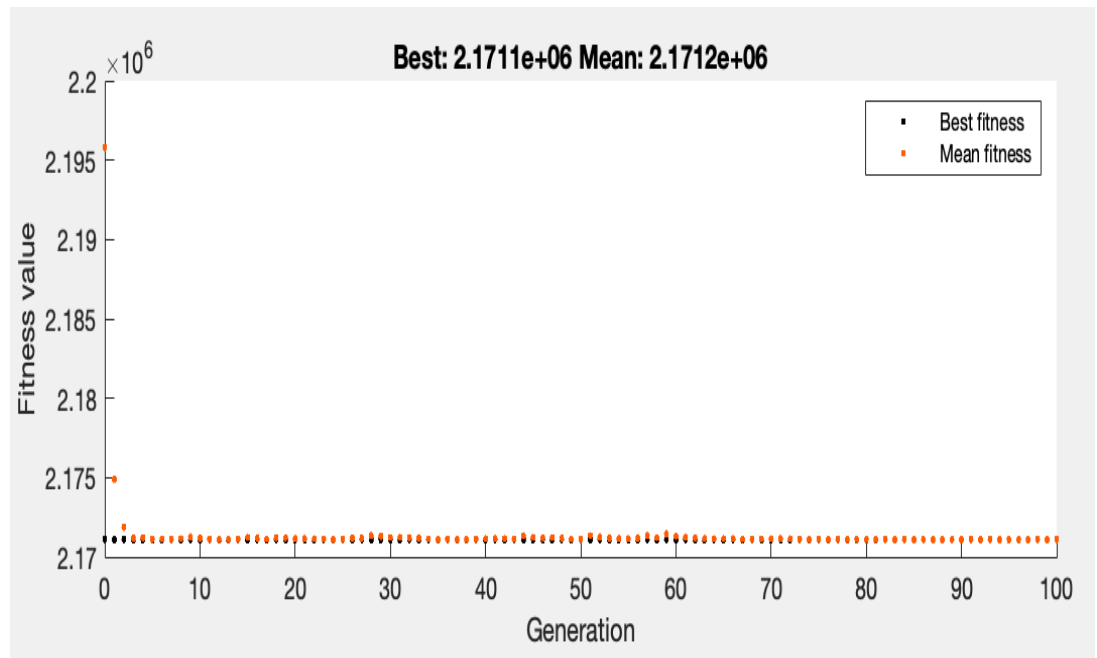


Figure 4.3: Genetic algorithm simulation (Base Scenario)

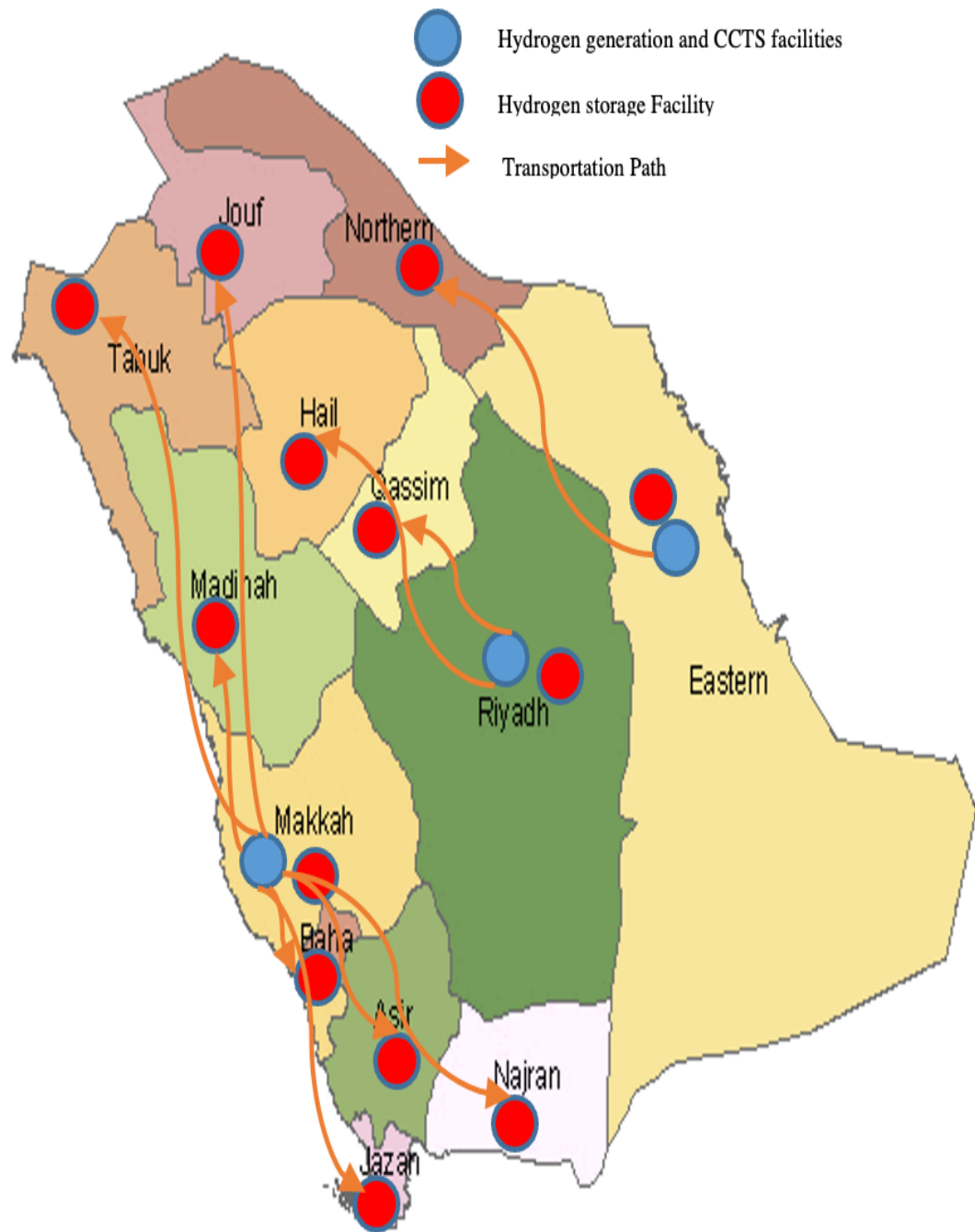


Figure 4.4: Optimal operation of electrolysis-based hydrogen supply-chain considering optimal power flow (Base Scenario)

4.2.3 MODIFIED SCENARIO: LOAD INCREASE

In this modified scenario, the hydrogen demands for Jazan and Najran have been increased by 30% and Table 4.6 depict this change. The following outcomes have been obtained

- 1- Riyadh, Eastern, and Makkah are still the only generation regions and the main suppliers to other regions.
- 2- Riyadh will continue generating 22,121 kg/d of hydrogen in which 17,932 kg/d will be for local supply and 1,724 kg/d for Qassim in addition to 1,597 kg/d for Hail.
- 3- Eastern will continue as well generating 9,031 kg/d in which 8,397 kg/d for local demand and 664 kg/d for Northern.
- 4- Makkah, however, will increase its generation to 21,890 kg/d in which 11,809 kg/d for local supply and remaining for remained regions.
- 5- Also, each region will contain a storage facility that accommodate the required demand each day for backup and emergency purposes.
- 6- Tables 4.7-4.10 present the mathematical model outcomes and Fig.4.6 depict the supply-chain optimality.

Table 4.6: Expected demand per region in 2030 (Modified Scenario#1)

Region	Demand (kg/d)	Region	Demand (kg/d)
Riyadh	17932	Najran	1667
Eastern	8367	Jazan	3560
Northern	664	Asir	615
Jouf	880	Baha	833
Hail	1597	Makkah	11809
Qassim	1724	Madinah	2051
Tabuk	1355		

Table 4.7: Supply-chain cost (Modified Scenario#1)

Term	Cost (\$/d)
CAPEX _{Generation & Storage}	669,795.83
CAPEX _{Transportation}	9,600.00
OPER _{Generation & Storage}	1,510,977.92
Fuel Cost	2,464.15
Labor Cost	2,483.95
Maintenance Cost	305.72
Miscellaneous Cost	112.10
Total Supply-Chain Cost	2,195,739.67
Power Cost (Consumption + Losses)	12,415.49
Total Cost	2,208,155.16

Table 4.8: Power flow results (Modified Scenario#1)

Term	Power (MW/d)
G1 Scaled Down Generation	159.99
G2 Scaled Down Generation	80.00
G3 Scaled Down Generation	48.50
G1 Actual Generation	38,838.85
G2 Actual Generation	19,420.69
G3 Actual Generation	11,773.03
Transmission Scaled Down Losses	7.51
Transmission Actual Losses	1,822.25
Hydrogen Power Demand	125.04
Transmission Losses Caused by Hydrogen Supply	3.18

Table 4.9: Power flow summary (Modified Scenario#1)

Bus	Pg (MW)	Qg (MW)	Pd (MW)	Qd (MW)	Voltage (p.u.)	Angle (rad)
1	38,838.85	8,483.60	2,196.38	0	1.05	0
2	19,420.69	4,160.90	14,308.34	3,083.03	1.02	-0.04758405
3	11,773.30	2,690.65	10,998.53	4,636.69	1	-0.08552650
4	0	0	4,389.87	-946.76	0.98	-0.12659168
5	0	0	1,098.25	388.41	0.98	-0.11521017
6	0	1,389.24	8,835.86	1,820.69	1	-0.28066808
7	0	0	0	0	0.99908	-0.23420532
8	0	1,606.90	4,950.71	0	1.01	-0.26981289
9	0	0	4,950.23	4,029.79	0.99398	-0.26866468
10	0	0	3,297.76	1,408.00	0.98297	-0.28665202
11	0	0	5,505.79	436.97	0.97892	-0.30557024
12	0	0	2,192.95	388.41	0.98294	-0.29648434
13	0	0	1,097.74	1,408.00	0.98378	-0.29026575
14	0	0	4,390.74	1,213.79	0.96778	-0.30298894

Table 4.10 Supply-chain summary (Modified Scenario#1)

Term	Value
NF _{Total}	55 units
NS _{Total}	13 facilities
NT _{Total}	36 units
FCon _{Total}	7,467.12 kg/d
T _{Total}	95.536 hrs. payment/d
D _{Total}	7006 km/d

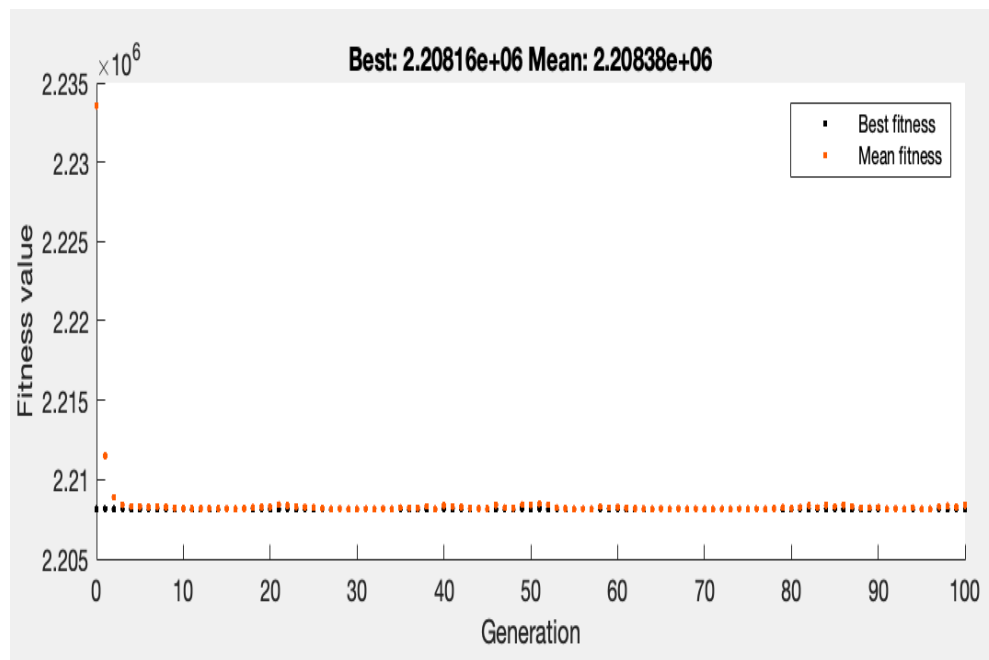


Figure 4.5: Genetic algorithm simulation (Modified Scenario#1)

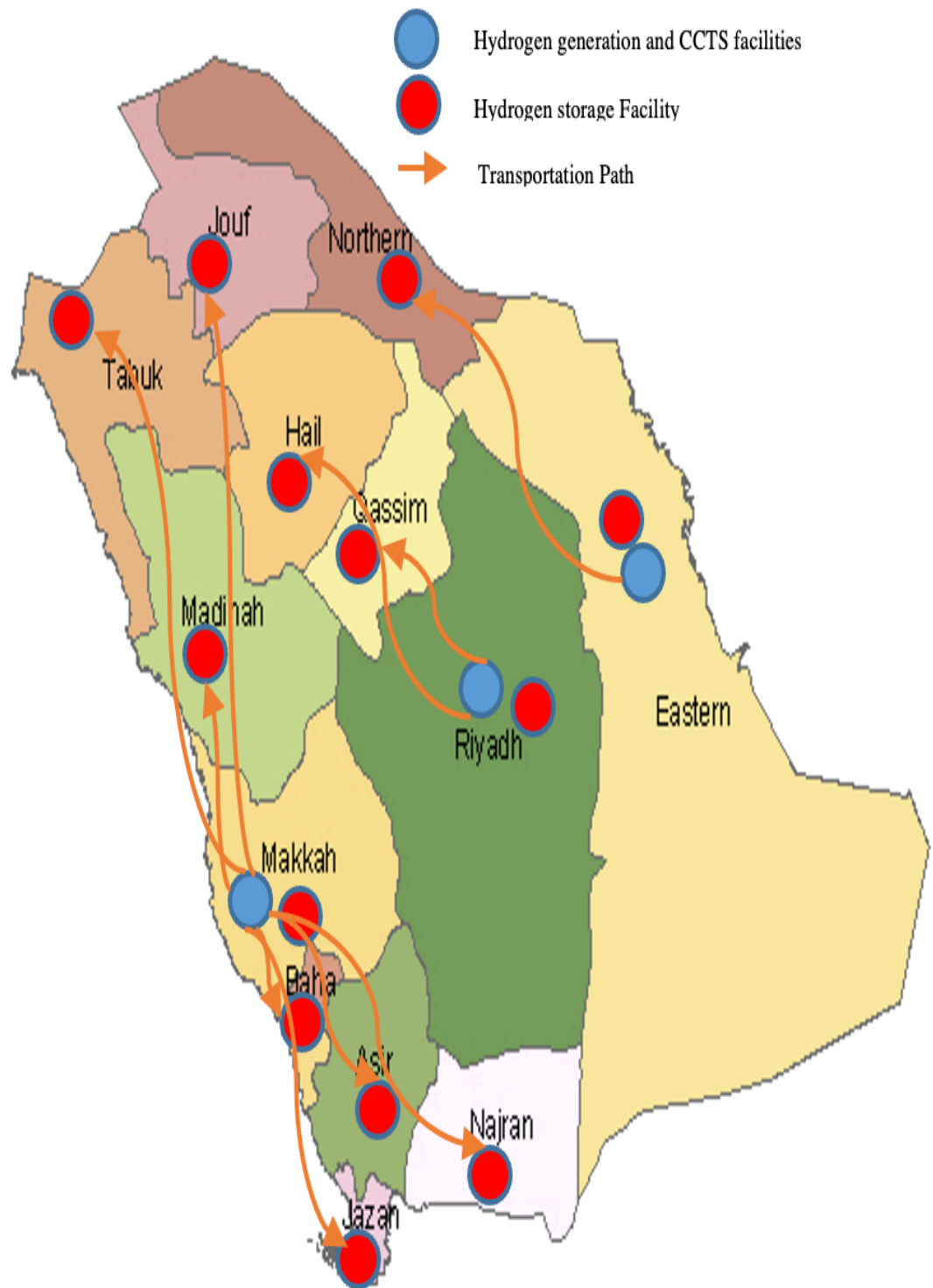


Figure 4.6: Optimal operation of electrolysis-based hydrogen supply-chain considering optimal power flow (Modified Scenario#1)

Table 4.11: Expected demand per region in 2030 (Modified Scenario#2)

Region	Demand (kg/d)	Region	Demand (kg/d)
Riyadh	17932	Najran	1282
Eastern	8367	Jazan	2738
Northern	664	Asir	615
Jouf	880	Baha	833
Hail	1597	Makkah	11809
Qassim	1724	Madinah	2051
Tabuk	1355		

Table 4.12: Supply-chain cost (Modified Scenario#2)

Term	Cost (\$/d)
CAPEX _{Generation & Storage}	658,723.21
CAPEX _{Transportation}	3,4134
OPER _{Generation & Storage}	1,457,051.14
Fuel Cost	4,517.6
Labor Cost	4,553.9
Maintenance Cost	560.48
Miscellaneous Cost	205.52
Total Supply-Chain Cost	2,159,745.847
Power Cost (Consumption + Losses)	12,181.11
Total Cost	2,171,926.96

Table 4.13: Power flow results (Modified Scenario#2)

Term	Power (MW/d)
G1 Scaled Down Generation	159.99
G2 Scaled Down Generation	80.00
G3 Scaled Down Generation	48.50
G1 Actual Generation	38,838.85
G2 Actual Generation	19,420.69
G3 Actual Generation	11,773.03
Transmission Scaled Down Losses	7.51
Transmission Actual Losses	1,822.25
Hydrogen Power Demand	122.00
Transmission Losses Caused by Hydrogen Supply	3.10

Table 4.14: Power flow summary (Modified Scenario#2)

Bus	Pg (MW)	Qg (MW)	Pd (MW)	Qd (MW)	Voltage (p.u.)	Angle (rad)
1	38,838.85	8,483.60	2,196.38	0	1.05	0
2	19,420.69	4,160.90	14,258.32	3,083.03	1.02	-0.04758405
3	11,773.30	2,690.65	11,048.55	4,636.69	1	-0.08552650
4	0	0	4,389.87	-946.76	0.98	-0.12659168
5	0	0	1,098.25	388.41	0.98	-0.11521017
6	0	1,389.24	8,827.76	1,820.69	1	-0.28066808
7	0	0	0	0	0.99908	-0.23420532
8	0	1,606.90	4,950.71	0	1.01	-0.26981289
9	0	0	4,950.23	4,029.79	0.99398	-0.26866468
10	0	0	3,297.76	1,408.00	0.98297	-0.28665202
11	0	0	5,505.79	436.97	0.97892	-0.30557024
12	0	0	2,192.95	388.41	0.98294	-0.29648434
13	0	0	1,097.74	1,408.00	0.98378	-0.29026575
14	0	0	4,399.76	1,213.79	0.96778	-0.30298894

Table 4.15: Supply-chain summary (Modified Scenario#2)

Term	Value
NF _{Total}	52 units
NS _{Total}	13 facilities
NT _{Total}	66 units
FCon _{Total}	13,689.72 kg/d
T _{Total}	175.15 hrs. payment/d
D _{Total}	7205 km/d

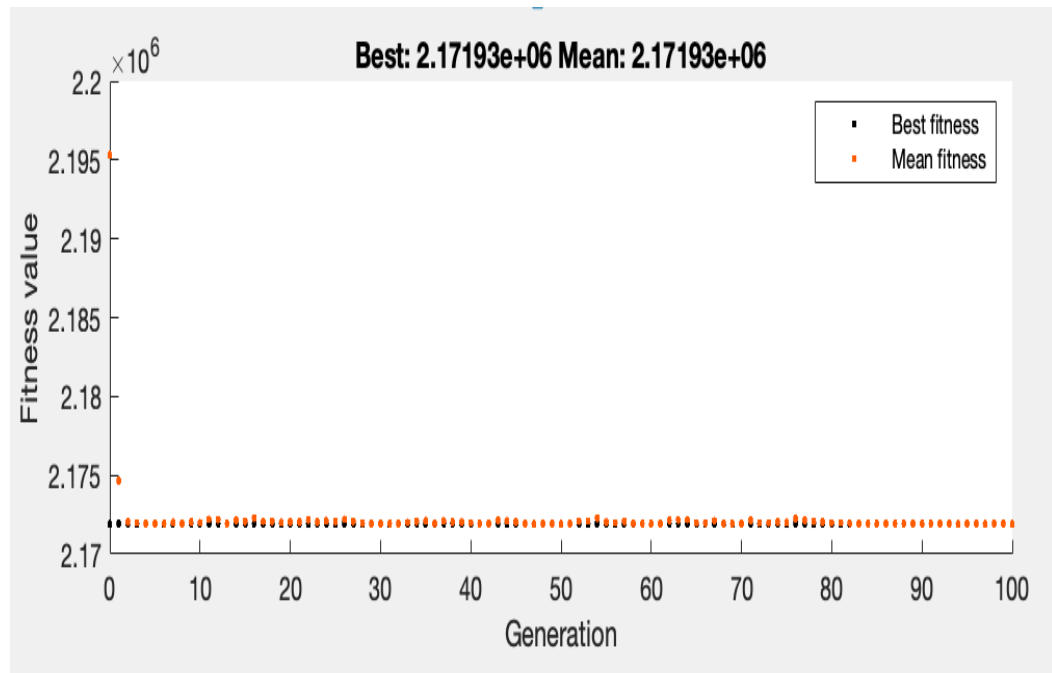


Figure 4.7: Genetic algorithm simulation (Modified Scenario#2)

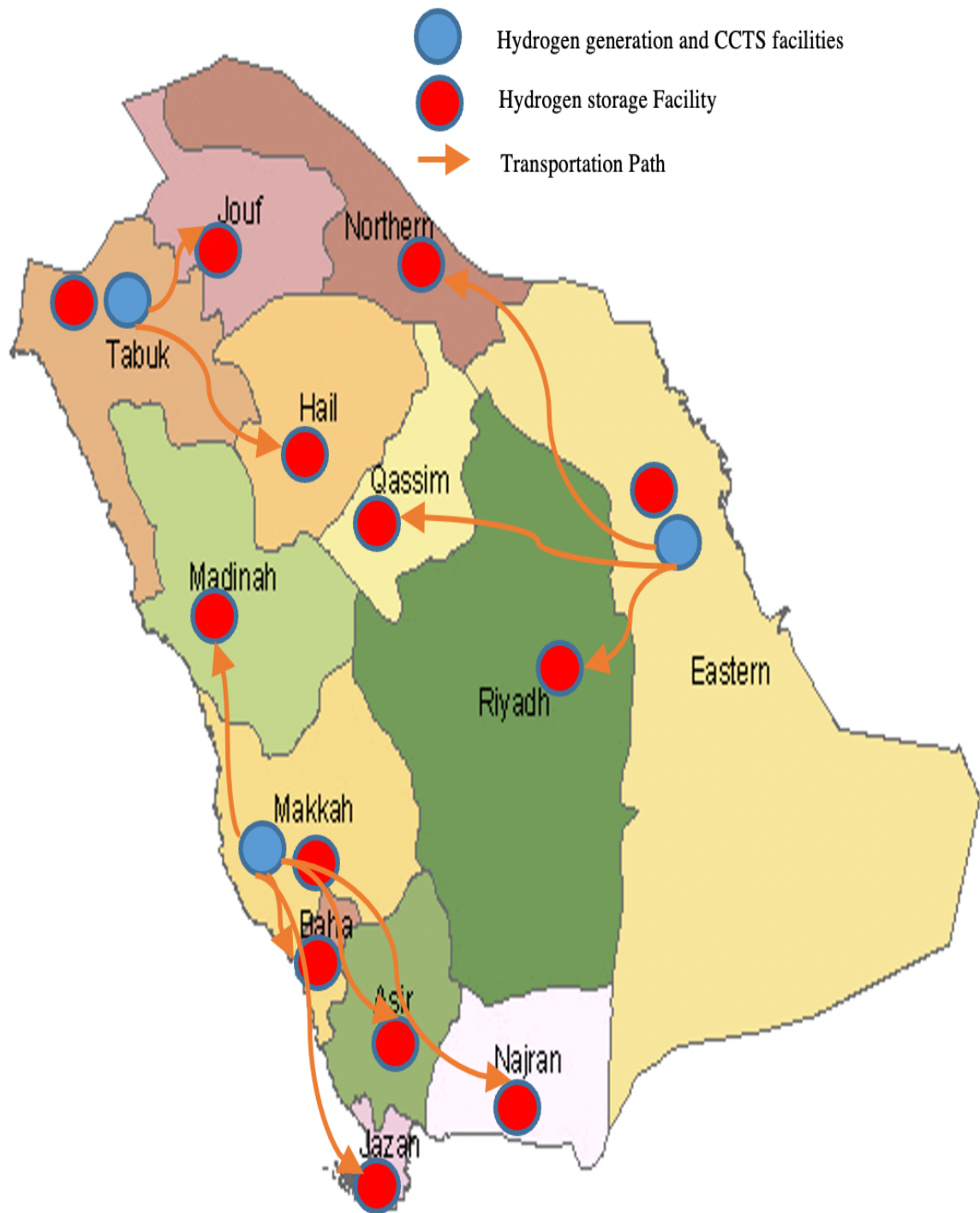


Figure 4.8: Optimal operation of electrolysis-based hydrogen supply-chain considering optimal power flow (Modified Scenario#2)

4.2.5 MODIFIED SCENARIO: GENERATOR RELOCATION

In this modified scenario, we will change the location of one generator and see the outcomes as well as the effectiveness of the module regarding any changes.

We will swap between Najran and Tabuk. Tabuk will be bus 1 and Najran will be bus 14. The following outcomes have been obtained

- 1- No changes to the supply-chain compared to the base scenario.
- 2- Only power terms changed which are highlighted on table 4.19 which is due to power grid's generators configuration change.
- 3- Tables 4.17-4.20 present the mathematical model outcomes and Fig.4.10 depict the supply-chain optimality.

Table 4.16: Expected demand per region in 2030 (Modified Scenario#3)

Region	Demand (kg/d)	Region	Demand (kg/d)
Riyadh	17932	Najran	1282
Eastern	8367	Jazan	2738
Northern	664	Asir	615
Jouf	880	Baha	833
Hail	1597	Makkah	11809
Qassim	1724	Madinah	2051
Tabuk	1355		

Table 4.17: Supply-chain cost (Modified Scenario#3)

Term	Cost (\$/d)
CAPEX _{Generation & Storage}	669,011.67
CAPEX _{Transportation}	8,800.00
OPER _{Generation & Storage}	1,476,260.80
Fuel Cost	2,258.80
Labor Cost	2,276.95
Maintenance Cost	280.24
Miscellaneous Cost	102.76
Total Supply-Chain Cost	2,158,991.22
Power Cost (Consumption + Losses)	12,119.67
Total Cost	2,171,064.89

Table 4.18: Power flow results (Modified Scenario#3)

Term	Power (MW/d)
G1 Scaled Down Generation	159.55
G2 Scaled Down Generation	80.00
G3 Scaled Down Generation	47.84
G1 Actual Generation	38,731.36
G2 Actual Generation	19,420.69

Term	Power (MW/d)
G3 Actual Generation	11,613.18
Transmission Scaled Down Losses	6.41
Transmission Actual Losses	1,556.08
Hydrogen Power Demand	122.00
Transmission Losses Caused by Hydrogen Supply	3.18

Table 4.19: Power flow summary (Modified Scenario#3)

Bus	Pg (MW)	Qg (MW)	Pd (MW)	Qd (MW)	Voltage (p.u.)	Angle (rad)
1	38,731.36	5,092.04	4,390.91	1,213.79	1.05	0
2	19,420.69	8,727.06	14,308.34	3,083.03	1.03	-0.04676625
3	11,613.18	2,896.86	10,998.53	4,636.69	1.01	-0.08227389
4	0	0	4,389.87	-946.76	0.9903	-0.11920340
5	0	0	1,098.25	388.41	0.9903	-0.10809562
6	0	-678.18	8,833.02	1,820.69	1	-0.26115377
7	0	0	0	0	1.0054	-0.21893700
8	0	732.52	4,950.71	0	1.01	-0.25432213
9	0	0	4,950.23	4,029.79	1.00219	-0.24959730
10	0	0	3,297.76	1,408.00	0.98982	-0.26737912
11	0	0	5,505.79	436.97	0.98249	-0.28610476
12	0	0	2,192.95	388.41	0.98529	-0.27522456
13	0	0	1,097.74	1,408.00	0.98903	-0.26829006
14	0	0	2,196.20	0	0.98974	-0.27168656

Table 4.20: Supply-chain summary (Modified Scenario#3)

Term	Value
NF _{Total}	54 units
NS _{Total}	13 facilities
NT _{Total}	33 units
FCon _{Total}	6844.86 kg/d
T _{Total}	87.575 hrs. payment/d
D _{Total}	7006 km/d

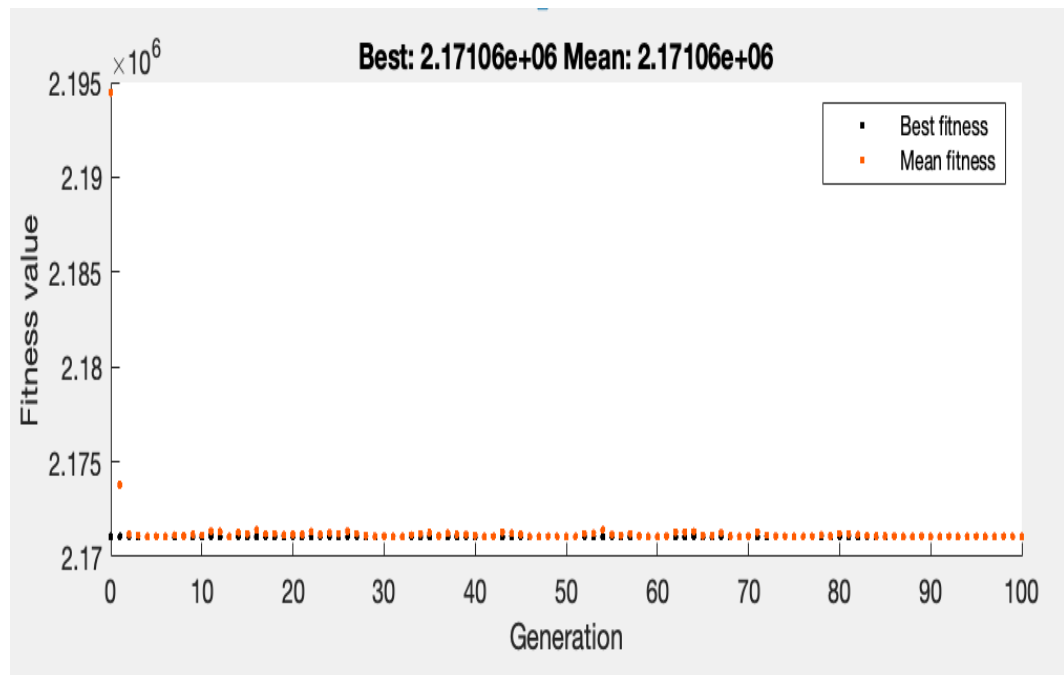


Figure 4.9: Genetic algorithm simulation (Modified Scenario#3)

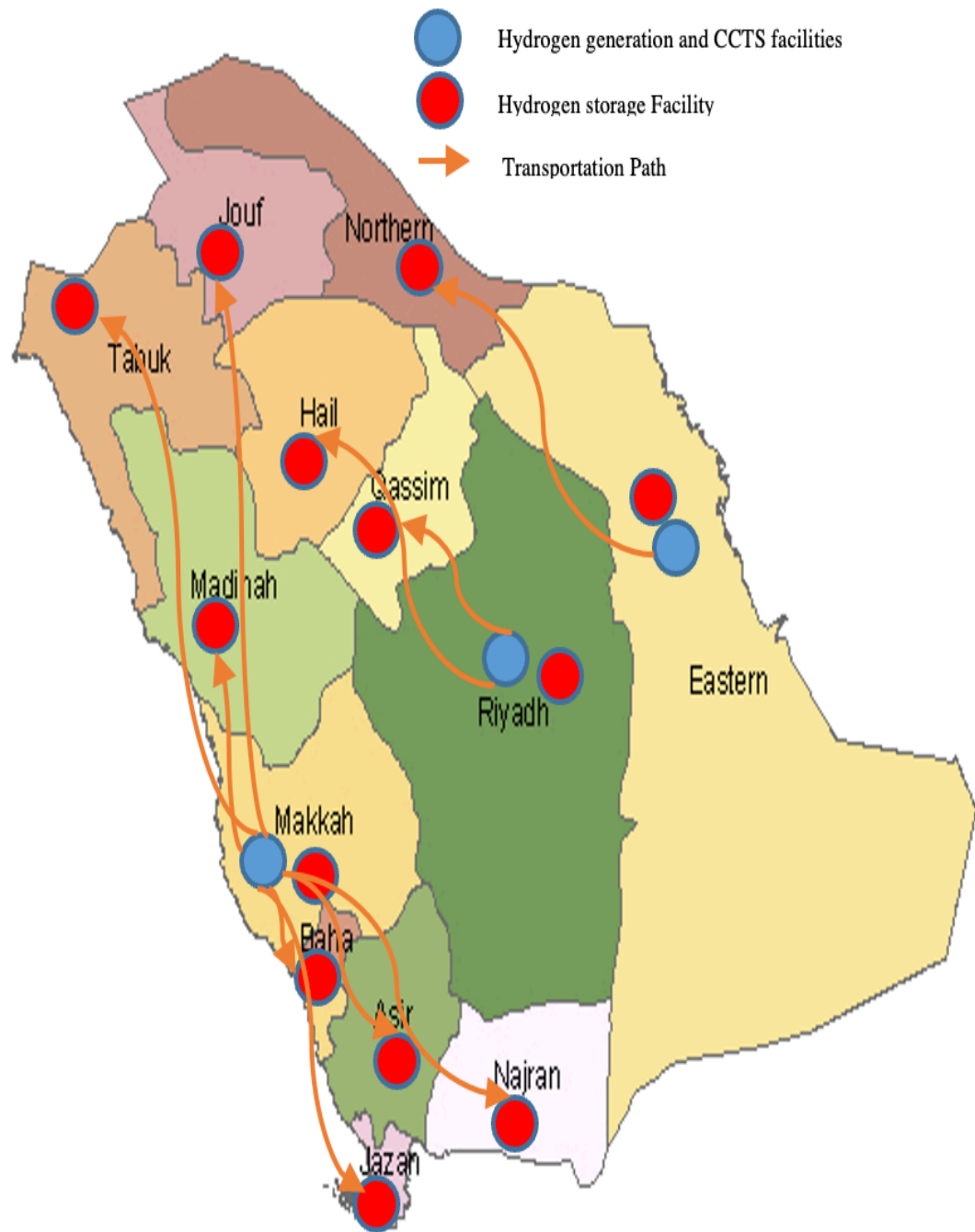


Figure 4.10: Optimal operation of electrolysis-based hydrogen supply-chain considering optimal power flow (Modified Scenario#3)

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS ABOUT THE MODEL

The mathematical model utilized and presented in this thesis is a comprehended model that can be utilized in real-life for the deployment of electrolysis-based hydrogen generation plants considering optimal power flow. The model takes into consideration many aspects for the deployment of the technology. It considers capital costs for generation and storage, capital costs for the transportation rental program, operation costs for generation and storage, fuel costs, labor costs, maintenance costs, miscellaneous costs, and power costs.

The model is subjected to several constraints that ensure the simulation to reality, and four scenarios have been implemented on the model to

verify its effectiveness and it has shown quick adoption and optimization to any input parameters change. In addition, the genetic algorithm utilized for solving the model showed high performance and solved the problem within 56 seconds considering population size of 200, generation of 100, and 1×10^{-1000} tolerance under MacBook Pro (13-inch, M1, 2020) using Matlab R2021a.

5.2 CONCLUSIONS ABOUT THE RESULTS

As discussed previously, the mathematical model has been implemented on four different scenarios to verify its effectiveness; the base scenario for the expected demand in 2030 and three modified scenarios.

In the base scenario, the total expected cost is 2,171,103.20 \$/d which corresponds to 792,452,668.00 \$/y, where most of the cost has been contributed by the operating costs that equal to 1,476,260.80 \$/d which corresponds to 538,835,192.00 \$/y. In addition, one can notice that Jouf is supplied by Makkah instead of Riyadh while Riyadh is closer. However, this to ensure operations optimality and cost saving in which having Jouf supplied by Riyadh will force the addition of 1 unit that will only be utilized to cover 1 kg/d of hydrogen demand, that's why

Makkah has been assigned to supply that region with distance increase margin of 276 km compared to Riyadh and this will eliminate the need of addition of a generation unit to Riyadh and will contribute to the overall resulted cost.

In the first modified scenario, the total expected cost is 2,208,155.16 \$/d, which corresponds to 805,976,633.4 \$/y and operating costs are also the main contributors to this cost by 1,510,977.92 \$/d that corresponds to 551,506,940.80 \$/y. In addition, one can notice that the demand increase caused by the 30% increase of demand by Najran and Jazan caused production increase for Makkah by the same increase amount and the case for Jouf supply is as it was in the base scenario. Furthermore, the total expected cost increased by 1.71% compared to the base scenario.

In the second modified scenario, the total expected cost is 2,171,926.96 \$/d, which corresponds to 792,753,340.40 \$/y and operating costs are also the main contributors to this cost by 1,457,051.14 \$/d that corresponds to 531,823,666.10 \$/y. One can notice that an increase of approximately 0.04% in the total cost compared to the base scenario

which is due to an increase in transportation costs that have been accepted rather than accepting the penalization of 30% for region without close water supply.

In the third modified scenario, the total expected cost is 2,171,064.89 \$/d, which corresponds to 792,438,684.85 \$/y and operating costs are also the main contributors to this cost by 1,457,051.14 \$/d that corresponds to 531,823,666.10 \$/y. Also, one can notice that an increase in the power cost by approximately 0.06% which is after the relocation of one generator and this is because of that the new generator place will supply Makkah instead of Najran which has shorter distance.

5.3 CONCLUSIONS ABOUT CO₂ REDUCTION

As discussed previously, one of the main goals of this thesis work is CO₂ emissions reduction that are contributing heavily to many environmental issues. To quantify the amount of CO₂ that has been deducted by the utilization of this hydrogen technology as an alternative to petrol and diesel, approximately 160 lbs. of CO₂/MMBtu which correspond to 0.2476 kg of CO₂/kWh is emitted when petrol and diesel burns [37].

Since our hydrogen load is equal to 51,847 kg/d which correspond in energy content to approximately 142,579.25 kg/d for petrol and diesel, then the total CO₂ reduction that will be encountered considering our base scenario in the analysis and results chapter will be roughly 423,631.47 kg of CO₂/d.

5.4 RECOMMENDATIONS

As argued previously, hydrogen technology is one of the most promising technologies that exist, and the deployment of this technology will help the reduction of CO₂ emissions and support the environment as well as the well-being. In addition, the deployment of this technology in real-life is one of the hottest topics in the literature. Scientists, scholars, and researchers are encouraged heavily to contribute into this topic.

The model presented in this thesis showed a comprehended approach for the deployment of the technology in real-life. However, several recommendations can be brought on for others to move this topic forward, which are

1- The utilization of renewables generation within the system.

Renewables generation can play a great role in the CO₂ reduction within the environment and can help on the overall cost encountered when utilized on the optimal way.

2- Utilization of geographical area transportation infrastructure.

As it has been stated previously, hydrogen can be transported on multiple ways such as compressed gas or liquid. Therefore, studying the utilization of the existing transportation infrastructure within the geographical area, such as its piping, and adding it to the mathematical model can contribute and reduce the overall encountered cost.

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APPENDIX I

INPUT PARAMETERS

Term	Value	Remarks
PCF _{All}	2352.5 \$	Electrolyzer Capital Cost (\$) (1000 \$/MW) for production of 1,000 kg/d
SCF _{All}	17500 \$	Hydrogen Storage Capital Cost (\$) for 1,000 kg storage capacity
TCF _{All}	800 \$	Cost of Establishing (rent) Transportation Unit (\$) for 500 kg capacity
AC _{All Generation Plants}	3 years	--
AC _{All Storage Facilities}	3 years	--
AC _{All Transportation}	3 years	--
OT _{All}	365 d/y	--
UPCF _{All}	14.24 \$/kg	--
USCF _{All}	14.24 \$/kg	--
DWCF _{All}	26 \$/h	--
MCF _{All}	0.04 \$/km	--
TI _{All}	2.74 \$/Transportation Unit/d	--
LR _{All}	0.274 \$/Transportation Unit/d	--
OF _{All}	0.1 \$/Transportation Unit/d	--
Life Span	20 years	--
FCF	0.33 \$/km	--

APPENDIX II

DISTANCES BETWEEN CITIES

Tabuk	Madinah	Makkah	Baha	Asir	Jazan	Najran	Qassim	Hail	Jouf	Northern	Eastern	Riyadh	(km)
1283	838	866	876	950	1140	945	356	621	978	1052	410	0	Riyadh
1681	1233	1272	1282	1353	1547	1341	752	1017	1169	1040	0	410	Eastern
630	975	1419	1597	1862	2093	1997	804	551	186	0	1040	1052	Northern
465	811	1254	1432	1697	1929	1928	640	386	0	186	1169	978	Jouf
675	428	871	1049	1317	1546	1568	280	0	386	551	1017	621	Hail
939	521	854	882	1211	1401	1294	0	280	640	804	752	356	Qassim
1812	1197	907	584	256	332	0	1294	1568	1928	1997	1341	945	Najran
1678	1120	690	498	207	0	332	1401	1546	1929	2093	1547	1140	Jazan
1624	1011	637	332	0	207	256	1211	1317	1697	1862	1353	950	Asir
1306	693	303	0	332	498	584	882	1049	1432	1597	1282	876	Baha
1021	453	0	303	637	690	907	854	871	1254	1419	1272	866	Makkah
621	0	453	693	1011	1120	1197	521	428	811	975	1233	838	Madinah
0	621	1021	1306	1624	1678	1812	939	675	465	630	1681	1283	Tabuk

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