Addis Ababa University

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School of Electrical and Computer Engineering

Doctoral Program in Electrical Power Engineering

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Addis Ababa University
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Dissertation

On

Optimization of Security Constrained Economic Dispatch for Integrated Renewable Energy Systems

Dissertation submitted to school of electrical and computer engineering of Addis Ababa institute of technology in fulfillment of the requirements for

Doctoral Philosophy

In

Electrical Power Engineering

Supervisor: Dr. Getachew Bekele

Shewit Tsegaye
School of Electrical and Computer Engineering
Addis Ababa Institute of Technology, Addis Ababa University
tsegayshewit@yahoo.com

Declaration

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I hereby declare that this Ph.D. dissertation contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree. Except where otherwise indicated, this Ph.D. dissertation is my own original work.

Shewit Tsegaye Shewi 27/05/2022

Ph.D. Student Signature Date

As dissertation advisor, I hereby notify that I read and evaluated this Ph.D. Dissertation prepared, under my guidance by Shewit Tsegaye entitled “Optimization of Security Constrained Economic Dispatch for Integrated Renewable Energy Systems”. I recommend that it be accepted as fulfilling the dissertation requirement.

Dr. Getachew Bekele 27/05/2022

Advisor Signature Date

Addis Ababa University
Addis Ababa institute of technology
School of electrical and computer engineering

By Shewit Tsegaye Gebreslassie

This is to certify that the dissertation prepared by Shewit Tsegaye Gebreslassie titled “Optimization of Security Constrained economic Dispatch for Integrated Renewable Energy Systems” and submitted in fulfillment for the degree of Doctor of Philosophy (PhD) in Power engineering complies with the regulations of the university and meets accepted standards with respect to originality and quality.

Approved and signed by board of examining committee

	Name	Signature	Date
Dean, school of electrical and Computer engineering	Dr Bisrat Deresbssa		
Supervisor	Dr Getachew Bekele		Sep. 02, 2023
External Examiner	Prof. Lina Bertling Tjerberg	2023-08-24	
Internal Examiner	Dr Lebsework Negash		31/08/2023

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List of acronyms

ABC	Artificial Bee Colony
CRGE	Climate Resilient Green Economy
DG	Distribution Generators
ED	Economic Dispatch
EEP	Ethiopian Electric Power
EGA	Extension Genetic Algorithms
EPGA	Efficient Parallel Genetic Algorithms
ERES	Ethiopian Renewable Energy systems
GTP	Growth and Transformation Plan
HGA	Hierarchal Parallel Genetic Algorithms
HHNN-GA	Hybrid Hopfield Neural Network - Genetic Algorithm
HOMER	Hybrid Optimization of Multiple Energy Resources
IRES	Integrated Renewable Energy Systems
LCOE	Levelized Cost of Energy
LFC	Load Frequency Control
PDF	Probability Distribution Function
PV	Solar Photo Voltaic
RCGA	Rapid Chaos Genetic Algorithms
RES	Renewable Energy Systems
SAGA	Self Adaptive Genetic Algorithms
SCED	Security Constrained Economic Dispatch
SCED	Security Constrained Economic Dispatch
SDOA	Sensory Deprived Optimization Algorithm
SWERA	Solar and Wind Energy Resource Assessment

Nomenclature

a_i = Constant coefficient measure of losses

b_i= Constant coefficient representing fuel cost

B_{ij}= Active power loss coefficients

c = Weibull probability distribution factor

C_h = Hydropower generation cost of 1 MW

C_i = Constant coefficient including salary and wages

C_s= Solar power generation cost of 1 MW

C_{sp}= Solar power penalty cost

C_{sr}= Solar power reserve cost

C_w= Wind power generation cost of 1 MW

C_{wp}= Wind power penalty cost

C_{wr}= Wind power reserve cost

D_{RI} = Ramp rate limit

$f(x)$ = Function to be minimized

F_{Bth}= Biomass and waste to energy generation cost

F_{Gth}= Geothermal power generation cost

f_{pw}= Wind power probability distribution function

F_{sth}= Solar thermal power generation cost

F_{th}= Thermal power generation cost

$g_l(x)$ = Inequality constraints

G= Solar irradiance

G_{std}= Solar irradiance in a standard environment

$h_k(x)$ = Equality constraints

H_i= Average head

K = Number of equality constraints

k= Weibull probability distribution factor

L= Number of inequality constraints

N_{cc}= Number of Credible contingencies

N_G= Number of generating units

N_L = Number of security levels

N_{poz} = Number of prohibited zones

ϕ = Credible contingencies

P_{hr}= Hydropower output

P_{Bth}= Biomass and waste to energy power output

P_D= Power demand

P_{Gth}= Geothermal power output

P_{hgi} = Hydropower unit output

Pi_{max}= Maximum power generation limit

Pi_{min}= Minimum power generation limit

P_L = Power loss

P_{sg} = Solar power output

P_{sr}= Rated solar power output

P_{sth}= Solar thermal power output

P_{th}= Thermal power output

P_{wr}= Wind power output

Q_i= Discharge outflow

R_{ca}= Certain irradiance point set at 150 w/m2

S_l = Security level

Sl_{max} = Maximum Security level

SR_i= Spinning reserve limit

SSR= Maximum spinning reserve limit

V_i= Cut in wind speed

V_o= Cut out wind speed

V_r= Rated wind speed

V_{wt}= Forecasted wind speed

$x\ i\ (1)$= Security constraint

α = weight factors of unit costs between 0&1

φ = penetration rate

Abstract

One way of noticing the importance of electricity in our daily lives is when sudden interruption or blackout occurs. Considering a power system with Integrated Renewable Energy Systems (IRES) in which power supply interrupts every time it rains, such power system can cause serious damage to different types of loads connected, service centers and production plants. The main cause is the sudden increase or decrease in power output. According to Ethiopian electric power-network blackout report (2013-2016), 15 major blackouts were reported in three years’ time. Production plants and service centers were down for an average of four months a year. Natural incidents, equipment failure, and supply-demand mismatch collectively called contingencies cause most of these blackouts.

The first challenging aspect of power system operation is that electrical energy, unlike other commodities; is difficult to store in significant amounts. Implying that electrical power must be consumed at same time it is generated. For a reliable supply of power, it is therefore essential to maintain the balance between generation and demand. This aspect requires an accurate method of balancing generation and demand considering generation limits, transmission security constraints, contingencies, and uncertainties.

The other challenging aspect is the intermittency and variability of renewable energy sources. With increasing emphasis on improving efficiency and utilizing more renewable energy to mitigate climate change effects, power industry is confronted with such generation–demand mismatch challenges. These challenges are related to intermittency and non-dispatch ability of IRES. One of the daily power-system operation tasks that coins these challenges is Security-Constrained Economic Dispatch (SCED).

SCED is a process of allocating generation levels to generating units to entirely and economically supply the load while satisfying security constraints. Practical power system economic dispatch is multi objective, constrained, and stochastic, as it has to consider the aforementioned challenges. Practically a solution method that can cope up with the varying generation is needed.

This Ph.D. dissertation presents hybrid Genetic Algorithm-Hopfield Neural Network (GA-HNN) based optimization of SCED for IRES that address power mismatch problems of the Ethiopian power grid. Hopfield neural network can learn the stochastic behavior of varying generation and genetic algorithm can improve the convergence of global maxima by both reproducing and mutation the top solutions.

This dissertation encompasses four main contributions. First, a review on recent trends and state of the art of SCED applied for renewable energy sources and hybrid systems is articulated. Second, development of global search algorithms that provide approximate solutions for SCED problem, and mathematical modelling of the objective functions of IRES is carried out.

Third, study and assessments of security parameters with credible contingencies and uncertainty involving determination of the effect of contingencies and security constraints corresponding to renewable energy sources is made. Finally, optimal generation dispatch of modified IEEE 118 bus system and Ethiopian renewable energy system using hybrid GA-HNN is presented.

According to the results obtained, hybrid GA-HNN helps to determine SCED global optimum solution of integrated, intermittent renewable energy systems. The obtained results include saving 0.519 million $/MW within 24 hours of operation at power loss of only 35.23 MW. This makes the proposed approach a strong financial solution in renewable energy markets. Utilizing hybrid GA-HNN resulted in the reduction of power mismatch by 23%. This mismatch enables power system operator deal with the unserved customers and unserved energy produce. Moreover, number of recursive blackouts were reduced by 12.36 % and execution time of the solution method by 56.89 %.

Keywords:

Artificial intelligence, Hopfield neural network, Genetic algorithms, hybrid Genetic Algorithm-Hopfield Neural Network, Renewable energy system, and Security constrained economic dispatch.

Publications

Journal Publications and Articles

1. Shewit Tsegaye and Fekadu Shewarega, "Recent-Trends-on-Security-Constrained-Economic-Dispatch-A-Bibliographic-Review" International Journal of Electrical and Computer Engineering 13(07):466-471, 2019. doi.org/10.5281/zenodo.3300384.
2. Shewit Tsegaye, Fekadu Shewarega and Getachew Bekele, "A Review on Security Constrained Economic Dispatch of Integrated Renewable Energy Systems", EAI Endorsed Transactions on Energy Web, European Union Digital Library, 2020. http://dx.doi.org/10.4108/eai.25-9-2020.166363.
3. Shewit Tsegaye, Fekadu Shewarega and Getachew Bekele, "Hopfield Neural Network-based Security Constrained Economic Dispatch of Renewable Energy Systems", EAI Endorsed Transactions on Energy Web, European Union Digital Library,2021. https://eudl.eu/doi/10.4108/eai.25-1-2021.168224 .
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1. Shewit Tsegaye, Fekadu Shewarega and Getachew Bekele, "Security Constrained Economic Dispatch of renewable energy systems", International Conference on Advancements of Science and Technology, ICAST 2020: Advances of Science and Technology, pp 361-375, Springer Nature, Cham https://link.springer.com/chapter/10.1007/978-3-030-80621-7_26.
2. Shewit Tsegaye, Fekadu Shewarega and Getachew Bekele, "Artificial Intelligence based Security Constrained Economic Dispatch of Ethiopian Renewable Energy Systems: A Comparative Study", International Conference on Advancements of Science and Technology, ICAST 2021: Advances of Science and Technology, pp 522-542, Springer Nature, Cham, https://link.springer.com/chapter/10.1007/978-3-030-93712-6_35.
3. Shewit Tsegaye and Fekadu Shewarega "Study of Third order model of Synchronous machine for hydro power plants", International Conference on Recent Trends on Electrical and Computer Technologies, Haramaya University, 2018. https://www.haramaya.edu.et/hit-hosted-an-international-conference/.

Other Academic Publications

1. Shewit Tsegaye, " Electricity from ERTA'ALE'S Magma: a road map to complete transition of thermal power plants" Lambert Academic publishing, ISBN :978-613-9-46408-1
2. S. Tsegaye and K. A. Fante, "Analysis of Synchronous Machine Excitation Systems: Comparative Study," International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, 2016 doi.org/10.5281/zenodo.1130957
3. S. Tsegaye and S.Haileslassie "Load based analysis of SPV WPS for arid areas and pastoral community", International Conference on Recent Trends on Electrical and Computer Technologies (ICRTECT 2018), 2018, Haramaya University, Haramaya, Ethiopia.
4. Shewit Tsegaye, K. A. Fante, Belachew Banteyrga "Hydro governor control of synchronous machines: MATLAB/SIMULINK based analysis" International GKEN multi-disciplinary conference and workshop (GKEN 2018), 2018, Jimma university, Jimma, Ethiopia.
5. Shewit Tsegaye, Sebhatleab H. "Solar photovoltaic water pumping system for arid areas and pastoral communities: case study of Aynalem, southern Tigray Ethiopia", International Symposium on Sustainable Water Resources Development (ISSWRD 2017), 2017. Arbaminch University, Arbaminch, Ethiopia.

Certificates and Awards

1. Certificate of competency in big data- General Level: International Institute of Online Education (IIOE), United Nations Educational, Scientific and Cultural Organization (UNESCO), International Center for Higher Education Innovation under the auspices of UNSECO (UNESCO-ICHEI), November 12, 2020.
2. Certificate of participation in the digital tour on "Renewable Energy for Economic Development" for Ethiopia: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bavarian Ministry of Economic Affairs, Regional Development and Energy, 15th of October 2020, Munich, Germany.
3. Certificate of Excellence in Regulation for Universal Access to energy-Master Level: European University Institute, Robert Schuman center of advanced studies, Florence School of regulation, Energy. 11 February – 24, June 2019, Florence, Italy.
4. Certificate of completion for successfully completing Open Africa Power- African module, Open Africa Power, Enel foundation, Strathmore University and Addis Ababa University, January 2019, Addis Ababa, Ethiopia.

5. Certificate for presenting a paper at a National conference on innovative research for sustainable development, May 2019, Dilla University, Dilla, Ethiopia.
6. Certificate for presenting a paper at the International symposium on sustainable water resources development, 2017, Arbaminch University, Arbaminch, Ethiopia.
7. Certificate for participating in workshop entitled “Publishing and Presenting”, Global Knowledge Exchange Network (GKEN).
8. Certificate for presenting research paper at the 1st National conference of Samara University, Samara, Ethiopia.
9. Certificate of Acknowledgment for presenting a paper in the 7th international GKEN multidisciplinary conference and workshop, Jimma University, Jimma, Ethiopia.
10. Certificate for presenting two research papers in the International Conference on Recent Trends on Electrical and Computer Technologies (ICRTECT 2018), 2018, Haramaya University, Haramaya, Ethiopia.

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CHAPTER 3. SECURITY CONSTRAINED ECONOMIC DISPATCH OF INTEGRATED RENEWABLE ENERGY SYSTEMS: APPROACHES

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Chapter 1. Introduction

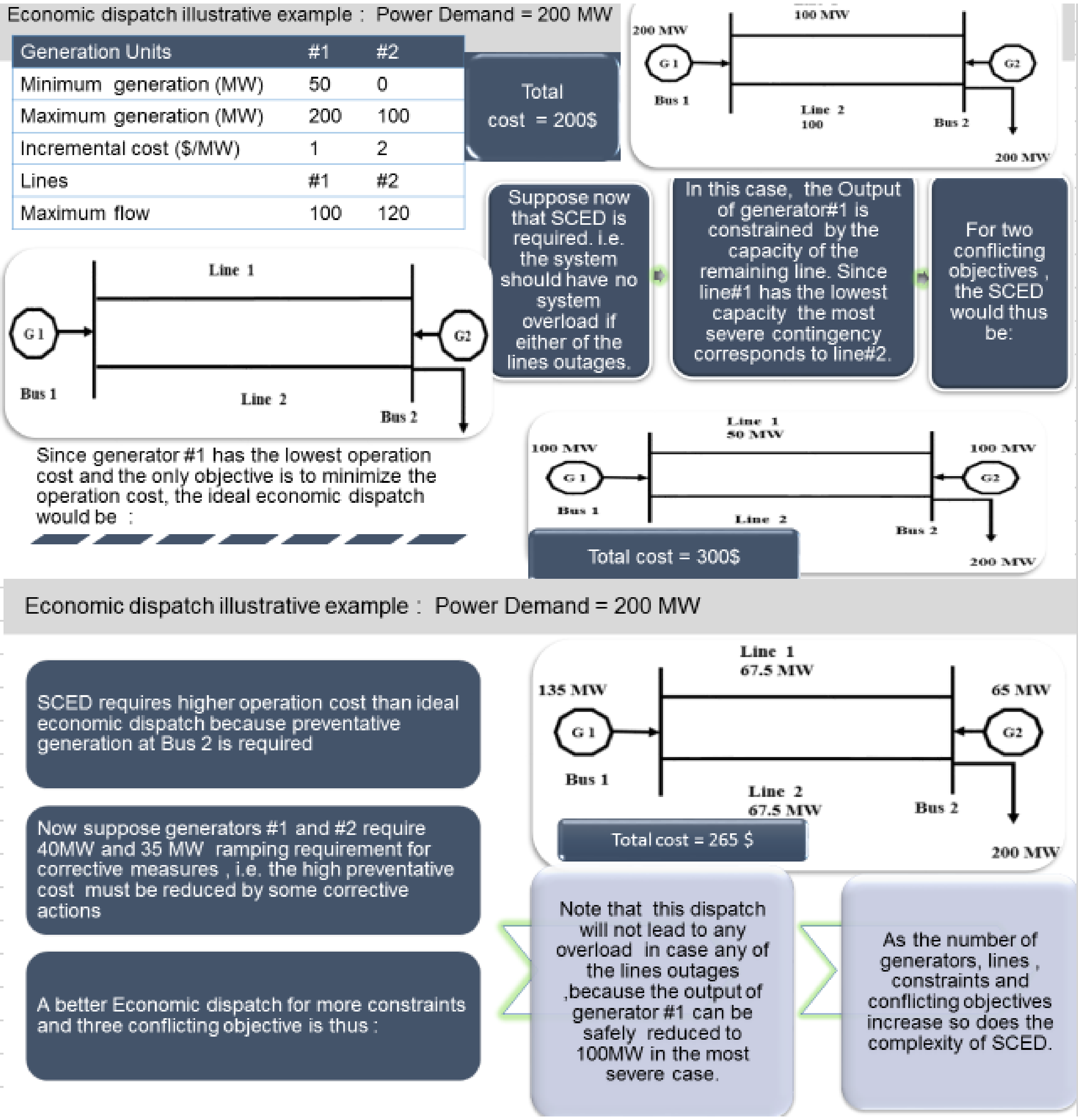
1.1. Research motivations

Renewable power generation helps countries meet their sustainable development goals through the provision of access to clean, reliable and affordable energy. Tens of gigawatts of wind, hydropower, geothermal, biomass and solar photovoltaic capacity are being installed worldwide every year into the renewable energy market. Intensive studies are being conducted on how to harness electrical energy from renewable sources of energy including the newly emerging Nanotube technologies [1]. After all these studies succeed and make a power system network composed of clean, secure, reliable and affordable energy sources, one needs to obtain a method of securing a reliable power system operation. Even though renewable energy sources are infinite and emission free, they pose technical and economic challenges to the secure and reliable traditional power system operation.

The intermittency characteristics of renewables can cause many sudden interruptions and unprecedented blackouts. These blackouts greatly threaten the social, regulatory and economic endeavors of energy dependent community. The main problem of power systems with integrated energy systems is that, electric power is insecure, non-reliable and faces many hindrances with regard to providing continuous service. Taking Ethiopian electric utility as an example, it can be seen that power service interruption happens 33% of full year service [2].

As electrical power cannot be stored in significant amounts, it needs to be concurrently consumed and generated. Implying that this aspect requires a method of instantly maintaining the balance between generation and load. The fluctuating nature and intermittent characteristics of wind and solar power generation, the problems associated with integrating renewable energy sources and managing power system stability are becoming more and more prominent challenges. Severe impacts caused by large power system contingencies demand the urgent need for high-efficiency and large-scale energy storage technology or accurate dispatch tools. Therefore, by applying energy storage technology, the variable wind and solar power outputs can be stored. This enables a power grid to be able to provide more stable power output that ensures prompt support to the active power, enhances the capability of grid frequency regulation, and leads to large-scale wind and solar generation connecting to grid both stable and reliable [3].

With expensive storage technology, accurate generation dispatch thus becomes a sole candidate to address the above challenge. Figure 1-1 illustrates the economic dispatch challenge [†] associated with storage constraint of electrical energy [4].



Economic dispatch illustrative example : Power Demand = 200 MW

Generation Units	#1	#2
Minimum generation (MW)	50	0
Maximum generation (MW)	200	100
Incremental cost ($/MW)	1	2
Lines	#1	#2
Maximum flow	100	120

Total cost = 200$

Since generator #1 has the lowest operation cost and the only objective is to minimize the operation cost, the ideal economic dispatch would be :

Suppose now that SCED is required. i.e. the system should have no system overload if either of the lines outages.

In this case, the Output of generator#1 is constrained by the capacity of the remaining line. Since line#1 has the lowest capacity the most severe contingency corresponds to line#2.

For two conflicting objectives , the SCED would thus be:

Total cost = 300$

Economic dispatch illustrative example : Power Demand = 200 MW

SCED requires higher operation cost than ideal economic dispatch because preventative generation at Bus 2 is required

Now suppose generators #1 and #2 require 40MW and 35 MW ramping requirement for corrective measures , i.e. the high preventative cost must be reduced by some corrective actions

A better Economic dispatch for more constraints and three conflicting objective is thus :

Total cost = 265 $

Note that this dispatch will not lead to any overload in case any of the lines outages ,because the output of generator #1 can be safely reduced to 100MW in the most severe case.

As the number of generators, lines , constraints and conflicting objectives increase so does the complexity of SCED.

Figure 1-1. Economic Dispatch illustrative example [5].

[†] The economic dispatch challenge regarding to the storage constraints of producing electricity i.e. electrical energy, unlike other commodities is difficult to economically store in significant amounts.

Conventional solution methods such as gradient method, lambda iteration method and Newton Raphson method complicate the economic dispatch problem as the number of power system design parameters increase [6]–[8]. For this reason, it is recommended to apply a computationally advanced solution method for the Security Constrained Economic Dispatch problem.

The other challenge relates to the integration of intermittent renewable energy sources. Non-dispatchablity and intermittency of wind and solar are challenges that cannot be ignored. Integrating these sources with dispatchable sources, providing storage and probabilistic forecast are their corresponding possible solutions. Accurate and timely implementation of economic dispatch alleviates these challenges. For example, integrating solar and wind with geothermal and hydro contributes to the stability of the electrical system by providing flexibility and reserve services[‡], which are products of timely implementation of economic dispatch [9].

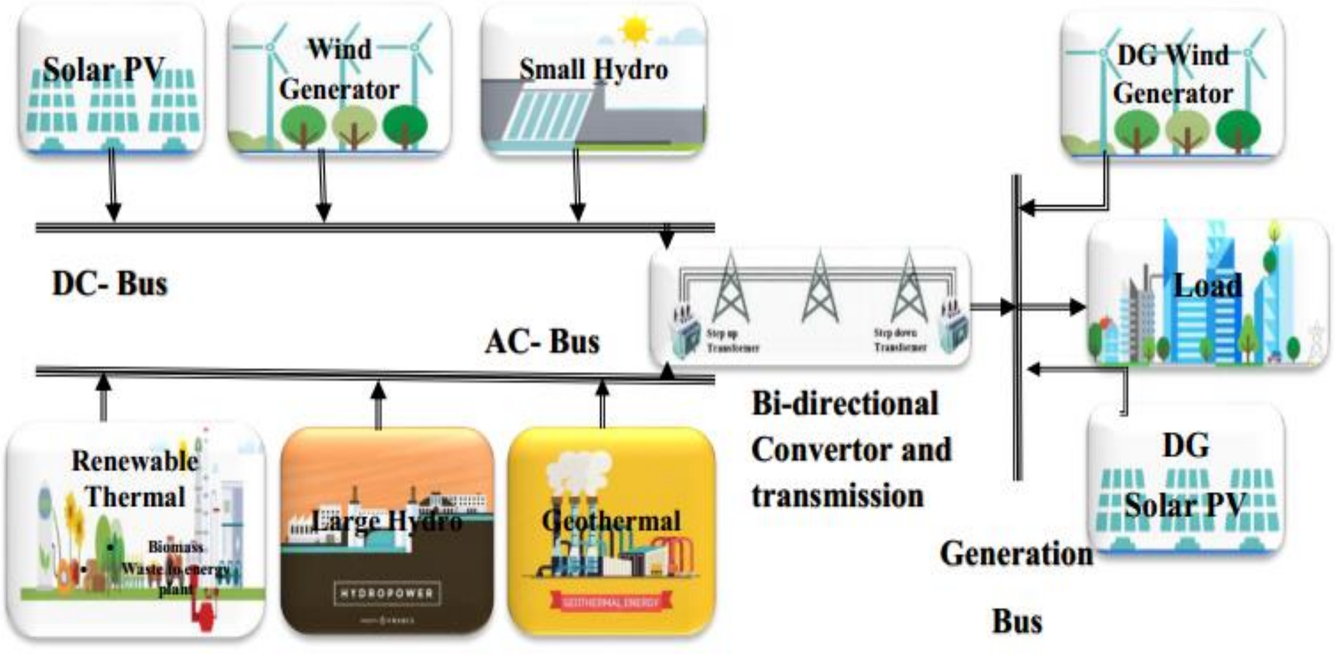


Figure. 1-2. Possible schematic diagram of renewables fed power system.

Therefore, one daily power systems operation task that coins these challenges is Security Constrained Economic Dispatch (SCED). SCED is a process of allocating generation levels to generating units to entirely and economically supply the load while satisfying security constraints. Simply put, to SCED means to economically order a generating unit to generate more or less power subject to its security

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[‡] Higher shares of renewables pose new challenges for power systems that lead to new challenges of energy security. This is because, higher penetration of renewable, or even complete introduction of renewables, demands new operational requirements such as ramp reserves, contingency reserves, accurate forecast, and instantaneous demand-generation balance

constraints. There is also additional importance of SCED in the new structure of the power industry that has pushed power systems to operate closer to their limits, due to market pressures and physical limitations in the transmission network. Here the argument for the importance of SCED hinges on the link among demand-supply imbalance, intermittency of renewables, blackouts and operational security needs.

There is growing evidence that unearths most blackouts of the Ethiopian power system are caused by poorly dispatched generating units [2] [10]. For one, under frequency and over frequency occur due to the imbalance between generation and load as presented in Figure 5-2, Chapter 5. As it can be seen from the Ethiopian blackout report, 2013 to 2016, all generating units of Fincha power station and all generating units of Amertinesh power station outaged due to under frequency[§][11]. The main reason for under frequency in turn is demand-supply imbalance, also known as power mismatch. In this regard, providing a contingency reserve could have saved the unserved demand due to the unit based partial outages.

Traditionally, the operating cost function subject to security constraints of each renewable energy resources was represented by a single line quadratic cost function. Practically, operation conditions and functions of generating plants require that the generation cost function be more complex and stochastic. Solving stochastic functions with their constrained multi-objective multi-variable optimization problems require converging artificial intelligence methods to locate a global optimum solution.

Artificial intelligence optimization methods utilized to solve economic load dispatch so far are; Hopfield neural network [1], hybrid genetic algorithm [2], particle swarm optimization and other various evolutionary algorithms. The literature listed in this dissertation encompasses different approaches to solve SCED of IRES and provide a comprehensive explanations of SCED. Hence, all the literature reviewed indicate the gaps and are used as input one-way or the other for this dissertation.

In order to minimize operating cost, and maximize the security level of IRES at the same time, this dissertation proposes artificial intelligence based multi-objective multi-variable optimization method called hybrid Genetic Algorithm-Hopfield Neural Network (GA-HNN)) as this method obtains global optimum solution with fast convergence. The strengths of Hopfield Neural Network and Genetic Algorithm make this hybrid method powerful in determining global maxima for multi-objective multivariable optimization problems [12].

[§] According to https://www.tandfonline.com/doi/abs/10.1080/15325008.2014.893545, the realistic and performance optimization inherent of the load frequency control (LFC) and security-constrained economic dispatch are considered without simplifying assumptions. For this purpose, modelling security-constrained economic dispatch as a discontinuous control action in the continuous frequency response model of a power system is well addressed

The main contributions of this desertion are:

- Providing state of the art bibliographic survey on recent trends of SCED with respect to different perspectives, from studies conducted within the last ten years (2008-2018), directly related to this particular topic.
- Presenting a selective overview of SCED for IRES. This contribution identifies the challenges posed to SCED due to intermittent RES penetration and investigates how the power dispatch of a power system is affected by RES penetration.
- Providing the prospects and challenges of using SCED based security analysis for the Ethiopian renewable energy systems. This encompasses multi-objective, multi-variable optimization of SCED using Hybrid Hopfield Neural Network and Genetic Algorithm.
- Introducing a hybrid artificial intelligence based optimization method for SCED of IRES called hybrid Genetic Algorithm-Hopfield Neural Network (GA-HNN) and applying this intelligent multi-objective optimization method based SCED for modified New England 39 bus system, NREL-IEEE 118 bus system and Ethiopian Renewable Energy Systems (ERES).

1.1.1. Problem statement

The Ethiopian government has set an ambitious goal to become a middle-income country by 2025. This goal includes aggressive electric power generation and connection targets. The current installed capacity is 4,206 MW with a composition of hydroelectric: 3,743 MW (89%), wind 337 MW (8%) and thermal 126 MW (3%). This power grid is a power system with higher penetration of renewable energy systems, 97% reported so far [13] [14]. According to blackout report data of the Ethiopian electric power network from 2013 to 2016, 15 major blackouts have been reported [2] [11]. These blackouts caused production plants and service centers to be down for an average of four months a year. Moreover, in the Ethiopian electric power network, the power supply interrupts every time it rains.

An estimated 85% of customers participated in an interview[**] responded that they are fed-up with the recursive power service interruptions and blackouts during holidays, weekends and heavy rain. Generally, considering a power system with IRES that take into account different constraints, limitations and intermittency characteristics, variable and affected by different factors, needs an accurate method of addressing supply-demand challenges.

How can a power system operator make these sources operate in harmony? How can a power system operator optimally dispatch such renewable energy systems? The problem statement of this dissertation is therefore addressed after answering these questions and a hybrid computational intelligence based optimization approach that can schedule a power system with integrated renewable energy generation while ensuring power system security is proposed.

1.1.2. Country description

Ethiopia (9°1′N 38°45′E) is a country in the Horn of Africa. With over 110 million population, it is the most populous landlocked country in the world, and the second-most populous nation in Africa after Nigeria. It occupies a total area of 1,100,000 square kilometers, and its capital and largest city is Addis Ababa [3] [4].

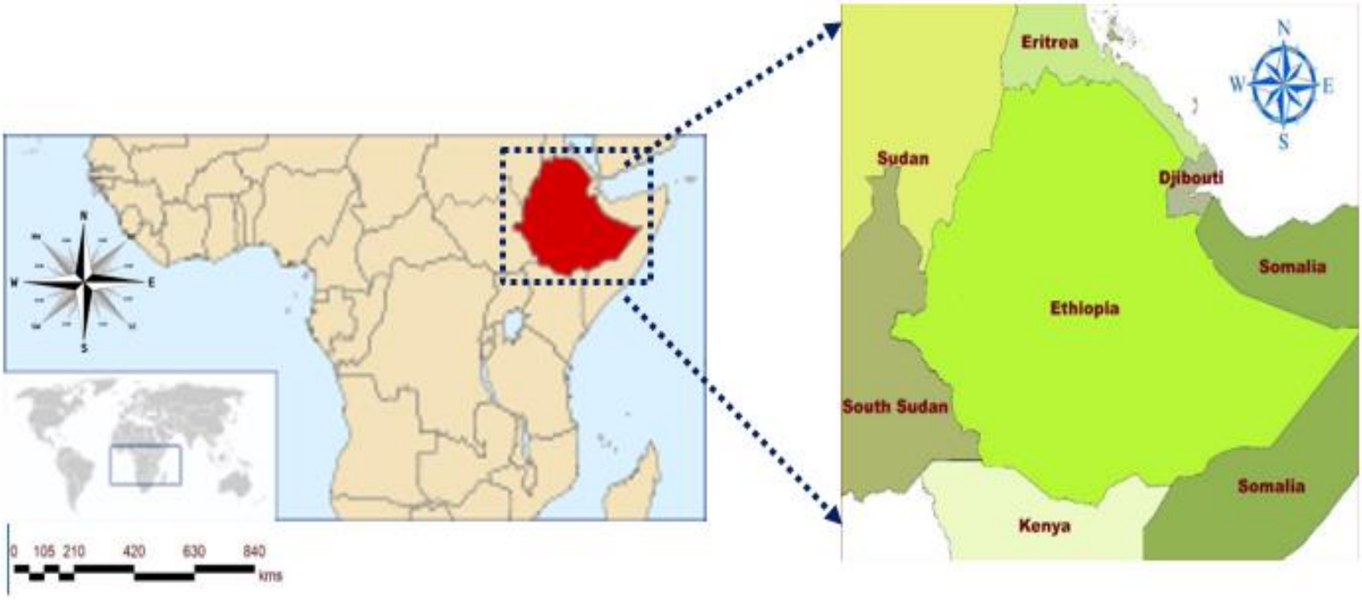

Figure 1-3. Country description

Ethiopia’s predominant climate is tropical monsoon, with a wide topographic-induced variation. There are 7 hours of sunshine per day [5]. Wind, solar, geothermal, hydro, and biomass are the abundant renewable

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[**] An interview carried out in the data collection, data analysis and verification stage. There are also supporting claims that can be heard from every Ethiopian Electric Utility customers. Though most customers did not gave us the main reason for the occurrences of recursive blackout and power surges, it can be simply understood that they have significant relation to poorly dispatched/managed power grid.

energy sources in Ethiopia. It is estimated that 11,105MW electric power can be generated from 14 hydropower plants, which is only less than 5% of the exploitable reserve.

It is also estimated that 1,520 MW electric power can be generated from 9 sites by wind turbines, which is only less than 1% of the exploitable reserve. Geothermal energy source accounts for generating of 1,270 MW of electric power from only 4 areas of the Ethiopian Great Rift Valley. Solar and biomass only account for 720 MW of electric power [2] [11] [15].

1.1.3. Research methods and proposed conceptual model

This dissertation uses primary data collected from power station control rooms, regional & national metrology agencies, and Ethiopian Electric Utility (EEU) for the first stage of planning. It also uses secondary data presented by NASA surface metrology and SWERA, auxiliary data collected and recorded from Ethiopian electric power plants.

The data parameters collected for this dissertation/ Ph.D. thesis include; forecasted load, interchange schedule, reserve requirements, transmission limits and parameters, generation cost offering, reserve limits, ramp rates and pre-scheduled generation output level. This is because the renewable sources considered as inputs to IRES include a combination of solar, wind, geothermal, hydro and biomass from municipal dry waste.

Data analysis was carried out after the relevant data parameters are collected and verified. Then there was the processing of the data to match with the mathematical model of the Security Constrained Economic Dispatch problem of IRES. The robustness of the formulated mathematical framework is first tested in NREL-IEEE 118 bus test system and modified New England 39 bus system. NREL-IEEE 118 bus system, modified New England 39 bus system are also utilized as case studies for the performance evaluation of the artificial intelligence based solution methods.

Then hybrid GA-HNN based SCED is applied on a physical power system called the Ethiopian Renewable Energy System to reduce its recursive blackouts. Computer-aided analysis for modelling and simulation of SCED was carried out using MATLAB and DIGSILENT power factory simulation platforms and the results are compared with previous literature respective to this particular topic. Diagram descriptions of the research approaches taken and conceptual model considered are respectively presented in Figure 1-4 and Figure 1-5.

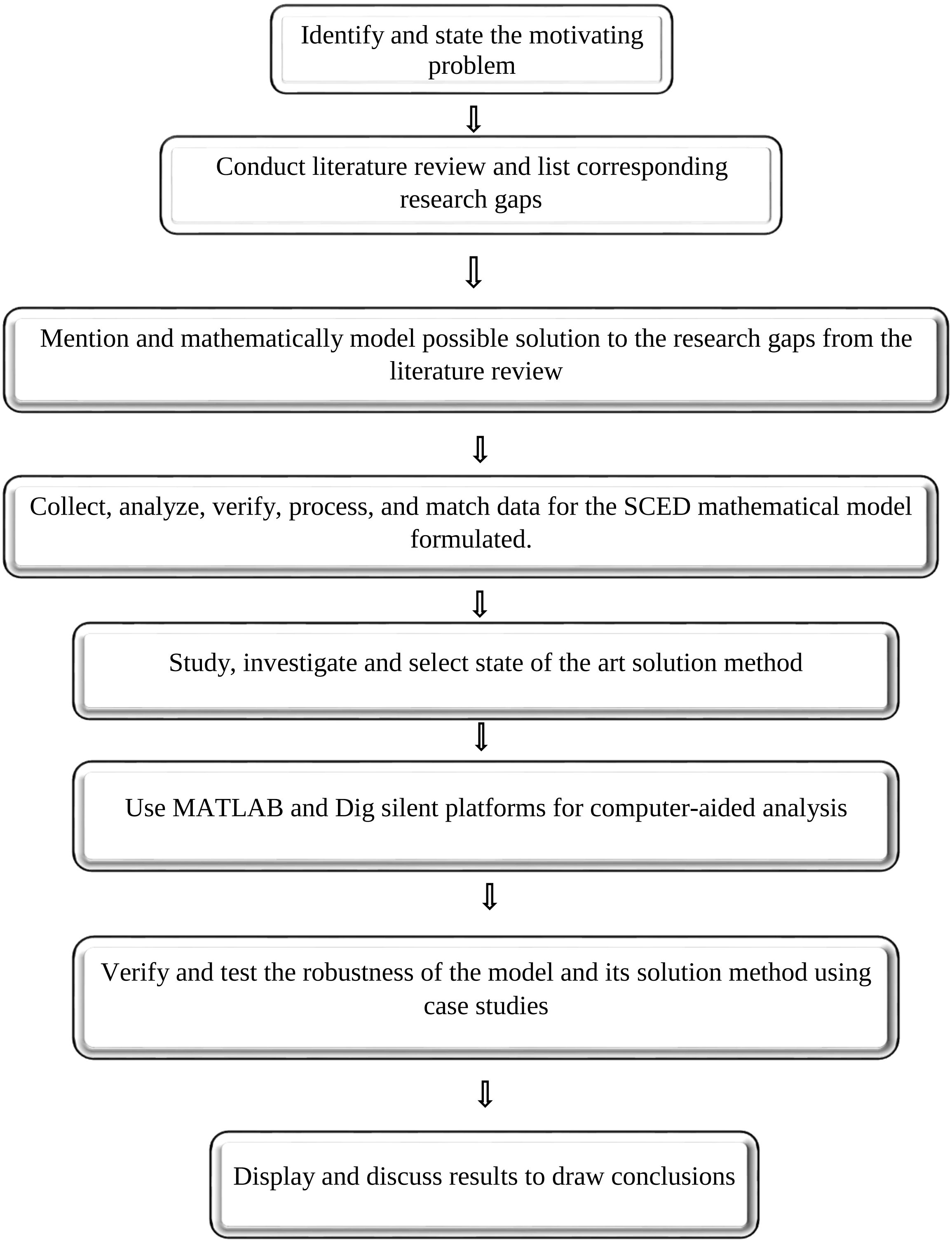


Figure 1-4. Research methodology

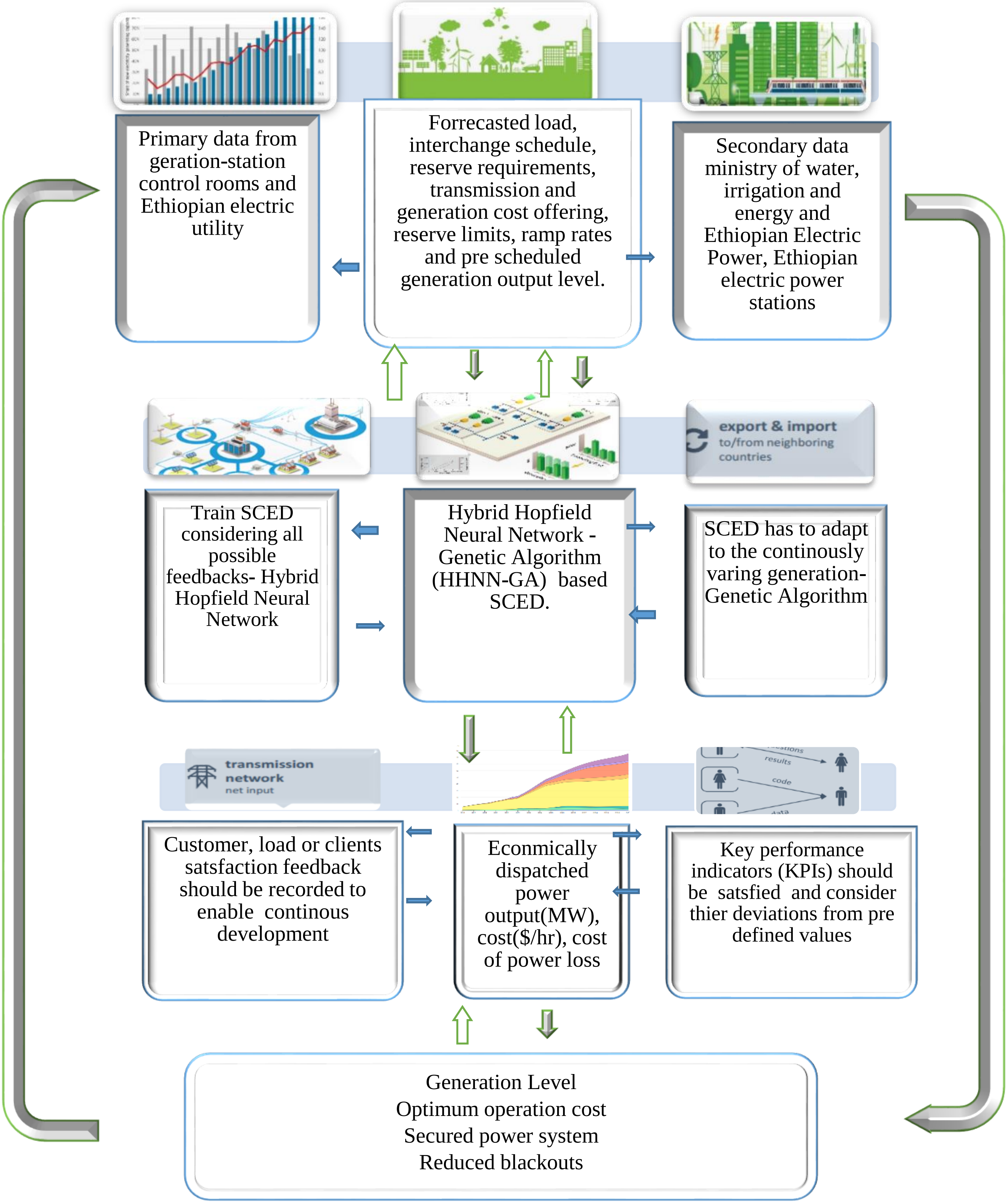


Figure 1-5. Proposed conceptual model

1.2. Research objectives

1.2.1. Main objective

The main objective of this Ph.D. dissertation is the optimization of SCED for IRES in general and of Ethiopian renewable energy systems in particular using artificial intelligence approach called hybrid Genetic Algorithm-Hopfield Neural Network (GA-HNN) approach.

1.2.2. Specific objectives

- To provide state of the art survey on recent trends of security constrained economic dispatch with respect to different perspectives directly related to this particular topic.
- To determine the optimal feasible generation dispatch of integrated renewable energy systems; this specific objective focuses on determining optimal generation cost of renewable generation units to secure power system operation.
- To solve security constrained economic dispatch problem with credible contingencies and uncertainty constraints; involving determination of the effect of contingencies and security constraints corresponding to the whole power system network.
- Developing global search algorithms, which can provide approximate solutions for a more accurate model of security-constrained economic dispatch problem, and mathematical modelling of the objective function considering security constraints are the foci of this specific objective.
- To apply a hybrid optimization method called hybrid GA-HNN to solve SCED of modified New England 39 bus system, NREL- IEEE 118 bus system and Ethiopian Renewable Energy Systems (ERES).

1.3. Thesis outline

Chapter 2.Background: Relevant literature on the background of renewable energy systems and integrated renewable energy systems are presented in this chapter. State of the art operation principle and the basic science behind common renewables with their maps of potential reserve regionally and nationally are discussed. This chapter also provides arguments on why we need renewable energy systems, what their challenges are in the electricity markets, and how these challenges can lead to recursive blackouts.

Chapter 3. Security constrained economic dispatch of integrated renewable energy systems: Approaches: After the groundwork connecting power system operation, economic dispatch, renewable energy systems and recursive blackouts is done, this chapter presents optimization approaches of Security constrained economic dispatch for integrated renewable energy systems. The need for optimization techniques in power systems, the link between optimization and economic dispatch and system security are discussed.

Chapter 4. Optimal Security constrained economic dispatch of integrated renewable energy systems: Methodologies. In this chapter, optimal Security constrained economic dispatch of integrated renewable energy systems methodologies are discussed. State of the art study on analytical methods, computational methods and hybrid methods are presented. The best and advanced solution methods for multi-objective multi-variable optimization such as genetic algorithms, Hopfield neural networks and hybrid Hopfield neural network-genetic algorithm are also presented in this chapter. Solving mechanisms, flowcharts, algorithms and methodologies of the selected solutions are in this chapter

Chapter 5. Case studies and test systems: Detailed and reliable public databases of Ethiopian power system are highly valuable for researchers to conduct studies on new technologies and to test new algorithms. In this chapter, two test systems named NREL 118 bus system (modified version of IEEE 118 bus system) and modified New England 39 bust system are presented. A physical power system called Ethiopian Renewable Energy Systems (ERES) is also discussed. Simulation assumptions, adoption strategies, simulation parameters, simulation result benchmarks from the two test-system are carefully studied before utilizing the solution method for a physical power system.

Chapter 6. Results and discussions: Results and discussions that connect the motivating problem of this dissertation and the proposed solution methods are the focuses of this chapter. SCED results of NREL 118 bus system (modified version of IEEE 118 bus system), modified New England 39 and Ethiopian Renewable Energy Systems (ERES) using multi-objective optimization, genetic algorithms, Hopfield neural networks and hybrid Hopfield neural network-genetic algorithm are presented. The physical interpretation of the results with respect to total dispatch level, total cost and system security are clearly presented in this chapter.

*Chapter 7. Concluding Remarks***:** This final chapter presents concluding remarks of Optimization of Security Constrained Economic Dispatch for Integrated Renewable Energy Systems. Summaries, contributions and future works are listed in this chapter.

Chapter 2. Background

2.1. Introduction

For decades, large power plants that use coal, heavy fuel oil, gas and hydro as prime movers, called non-renewable energy sources, produced electricity. Non-renewable energy sources have the disadvantages of using finite sources with unequal distribution of fuel, oil and coal supplies between regions. They emit greenhouse gasses or other wastes that make them air pollutants. Despite their advantages in presenting affordable, reliable and easily controllable technologies for electricity supply at a large scale, nonrenewable sources will eventually vanish. This is because sustainable, emission-free, renewable and reliable electricity is more desired recently. Nowadays, renewable energy sources such as wind, solar, biomass, waste and geothermal are increasingly being installed in modern power systems.

2.2. Literature review

2.2.1. Power system operation

A power system is considered to be secure at a given instance of time if it is able to withstand non-anticipated disturbances [16]. Depending on the ability of a power system network to withstand disturbances, five different states of operation are defined. Specifically, the power system is in a normal state if all operational limits are satisfied and is operating securely. In this stage, automatic voltage and frequency control take place to keep the system within the safety margins, following generation and load fluctuations. In a normal state, another goal is to minimize the operational costs [17].

If the system, operating with no limit violations, fails to operate within its limits after a disturbance, it is considered being in an alert state. In this state, security is at stake. To return the system to the normal state, preventive control actions need to be employed. If the system operates in the alert state and a disturbance that leads to operational limit violations occurs, the system enters the emergency state. In this case, emergency control actions are required to lead the system back to normal or at least to the alert state. If the aforementioned actions are not effective, the system enters the extremes state, where cascading events occur and parts of the system may be disconnected. To prevent widespread blackouts, actions like load shedding and controlled islanding should be taken. Finally, in the restorative state, corrective control actions are taken to reconnect the lost parts of the system and eventually operate again in a normal state [17] [18] [19].

In connection with these states of operation, there are three critical decision plans that depend on the length of planning time. The first decision plan consists of long-term plans ranging for years. Decision variables to be determined in long-term planning are plant capacity, plant type, and the number of power generating units to install. The second critical decision plan consists of medium-term planning in which its decision time ranges from days to months. Decision variables in medium-term planning include decisions on how to schedule and commit installed generation units. Finally, the third critical decision plan is called short-term planning that takes minutes to hours. The main goal of short term planning is to efficiently determine the amount of power that each scheduled and committed generating units need to produce to meet the real-time electricity demand.

In general, long-term power system planning is referred to as the power expansion plan, medium-term power planning is identified as the unit commitment and maintenance scheduling, and short-term power system planning is called the economic dispatch or generation to demand allocation plan. Power system states of operation are to be dealt with their corresponding decision plans. If there is a problem with the decision and operation plans, it will trigger one of the operation states of the power system operation [17][18].

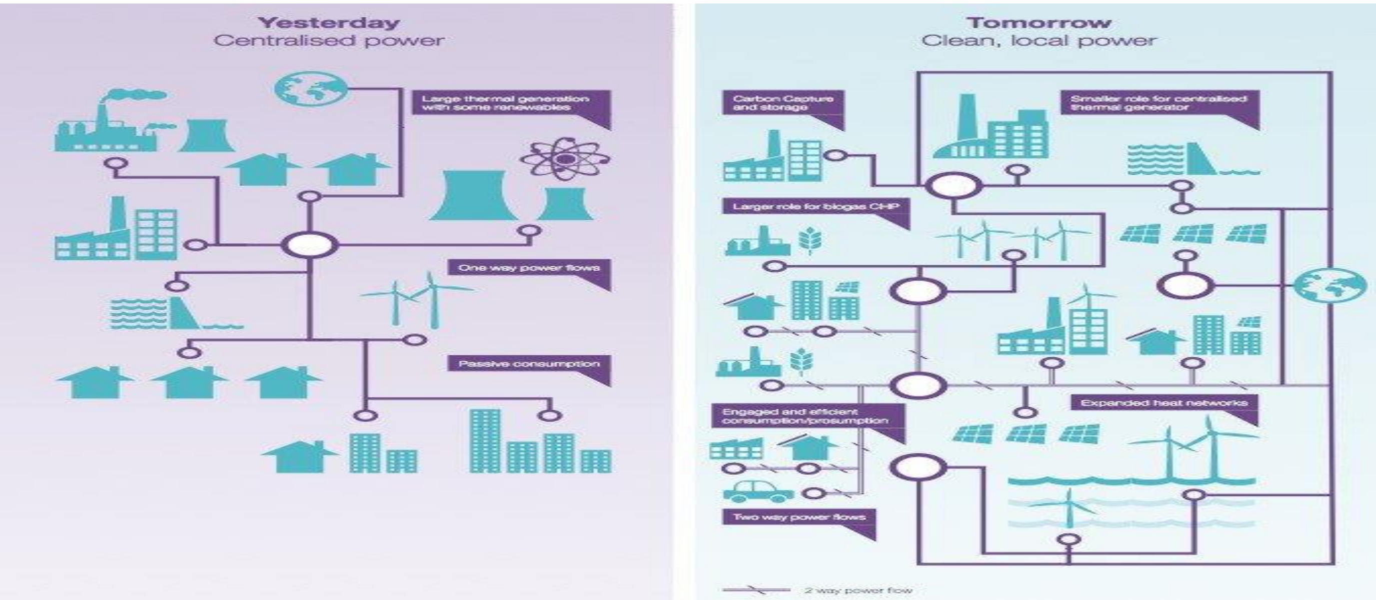


Figure. 2-1. The structure of future power systems (Power systems of integrated renewable energy systems) [20]

2.2.2. Economic dispatch and power system operation

Power system operation is critically dependent on the capabilities of generators for balancing the load. Practically, power system operation is never at its equilibrium. The stochastic nature of the demand, unprecedented equipment failures, and stochastic power generation are the main reasons for unbalanced, unreliable and insecure power system operation.

Due to the diversity in operational properties, involved power generating units in a power system network, scheduling and committing these generating units is required based on load forecast, economic characteristics, and technical specifications of the generating units. This involves calculating optimal power generation level called unit commitment and optimal loading of selected generating units called economic dispatch (ED). The main difference between economic dispatch and unit commitment[††] is that, economic dispatch assumes there are a set of committed units already connected to the system and unit commitment commits the generating units. ED performs the actual distribution of total load between committed units, which is optimized for each operating state while considering all economic and technical aspects of the units.

The cost component that is the most important in the economic dispatch problem is called operation cost. When continuous and uninterrupted power supply service is required, power security of the operating system must be ensured in each dispatch interval. This can be accomplished by either considering the security constraints of the economic dispatch problem or formulating the security-level objective function of the system. When an economic dispatch problem subject to security constraints is formulated, it is identified as Security Constrained Economic Dispatch (SCED).

When stochastic power generation, renewable generation, such as wind and solar are part of the power system/grid portfolio, the SCED problem becomes highly challenging due to intermittency, variability and limited predictability of these energy systems. In power system operation, the optimal allocation of power output among the committed generating units considering economic and technical constraints is one of the most important optimization problems. Considering a power plant having different operation cost curves, different electrical distance from the load and different characteristics make SCED a more challenging optimization problem.

2.2.3. Power system security analysis and economic dispatch

Power system operation demands a higher degree of security in order to keep the system operating satisfactorily while considering economic aspects. To do this, dynamic security analysis that evaluates time-dependent transition from the pre-contingent state to the post contingent state should be incorporated into the SCED problem. This kind of dynamic security analysis is introduced to the economic dispatch study of an electric power system, in the form of a security constraint that has to be satisfied. Dynamic security constraints are derived for each contingency to be considered in the operating power system.

[††] Unit Commitment (UC) is an optimization problem used to determine the operation schedule of the generating **units** at every hour interval with varying loads and generations under different generational, environmental and technical constraints.

In addition, the security constraints imply system performance evaluation of all possible postulated and credible contingency. In order to determine credible contingencies, the following classifier equation is used.

$$\phi(x) = \omega^T(x) + \phi_0 \tag{1-1}$$

The system is considered to be secured if $\phi \geq 0$. SCED determines a feasible minimum cost operating point such that in the event of any possible contingency, the post contingency states will remain secure, or within the pre-defined operating limits. Theoretically, the total number of N−1 security constraints is very large and equals n (n−1) for the system with n transmission and transformer branches. Practically, power transmission systems are usually designed within the capacity of the system load and generation. It is not necessary to incorporate all the N−1 security constraints into the calculation model directly. To detect all the possible over constrained cases, which must be considered, a quick contingency analysis for outages must be performed.

For each contingency, the equality and inequality constraints corresponding to that operating condition must be included in the economic dispatch problem formulation. For example, when outages of transmission lines are considered, a new set of equality and inequality constraints are required based on the contingency cases. SCED considers key system operation constraints, like power balance constraint, reserve requirement constraints, transmission security constraints, and generation limitations.

SCED is used in real-time, intra-day and day-ahead, to generate forward generation dispatch and price signals. The look-ahead time dispatch varies in different markets, from 5 minutes to 24 hours depending on objectives and the characteristics of the fleet. When SCED co-optimizes energy and ramp products, besides energy dispatch and costs, it also provides ramp assignments and ramp costs. Generation dispatch is restricted by the ramp rates. When a cheaper unit is ramp constrained, a more expensive flexible unit sets a higher energy cost.

When SCED produces enough ramping capability in the power system network to meet the ramping requirements, the ramp price is set to zero. In such cases, the ramping costs are relied upon to supply energy resources with the incentive to follow dispatch instructions. When the energy price increases, resources with an incremental cost less than the energy price have the upper hand to increase output so as to maximize their revenue. This effectively provides a price incentive for quick start units to be called first. Conversely, when energy prices decrease, resources producing energy at an incremental cost that is higher than the energy price have an incentive to decrease output.

A positive ramp price results when there is insufficient ramping capability in the system to meet a defined ramping requirement. Ramping costs can incentivize resources, both online and offline, to respond to the system's ramp needs depending on the look-ahead time. Overall, SCED not only generates efficient generation dispatch but also provides associated cost signals to encourage generating units to follow dispatch and help address system reliability needs.

This dissertation assumes generating units both committed and planned to be committed to provide energy and ramping capability. These concepts can be expanded to ramp reserves that are committed based on a longer look-ahead interval. Hence, result in additional unit commitments to provide the required ramping capability when necessary. Such dispatch prototype can be adopted from the PJM AS[‡‡] products where generating units are committed ahead of the operating hour to provide those services.

2.2.4. Security Constrained Economic Dispatch

In power system operation and planning the most frequently asked question is, what should the output power committed at each generating unit be during each dispatch such that to ensure a secure power supply for a specific demand in the most economical way? [17] [21]. It is possible to answer this question by security-constrained economic dispatch. SCED is the process of allocating generation levels to the generating units so that the system demand can be supplied entirely and economically while satisfying security constraints [22] [7].

Some methods such as the iterative method, gradient-based techniques, interior points method, linear programming and dynamic programming have been used to solve this problem [17] [22] [23]. SCED has been studied as Security Constrained Optimal Power Flow (SCOPF) and there are still no clear differences between them [24] [25]. Alizadeh et al [26] clearly articulated the definitions, terminologies and discussed the latest flexibility treatments in their review. The state-of-the-art research related to multi-objective evolutionary algorithms (MOEAs), Economic Dispatch (ED), Dynamic ED problems, ED problems incorporating wind power, ED problems incorporating electric vehicles and ED problems within micro-grids are surveyed in [27].

Several authors studied SCED with the perspective of multi-objective optimization problem [27] [28] [29] [30] while others approached it with the perspective of stochastic programming[9] [31]. Regardless of the differences in terminology, these authors have chronicled the major developments of optimal loading and generation scheduling [32].

[‡‡] PJM Interconnection LLC (PJM) is a regional transmission organization in the United States. It is part of the Eastern Interconnection grid operating an electric transmission system & most of its benchmarks are considered to be adopted to modernize the striving Ethiopian power grid.

From the decomposition of SCED optimization problem point of view, there has been a development towards Optimality Condition Decomposition (OCD) [7] and improved Bender's decomposition with contingency filtering techniques [7]. A substantial number of articles reported SCED in the perspective of artificial intelligence, integrated renewable energy source, and post-disturbance corrective actions [33]. Researchers and graduate scholars are recently being interested in reviews, surveys, and critics of a particular topic to help them understand state-of-the-art and identify the research direction of that particular topic. The contribution of this review is, therefore, the presentation of survey of papers, books and reports published in the years 2008 through 2019 with their strengths and weaknesses to identify research gaps. To do this, the literatures are grouped into three important areas of study and these are:

- SCED of power system with IRES
- SCED with post contingency corrective actions,
- Artificial intelligence-based SCED

2.2.5. SCED of Power Systems with respect to IRES

The contribution of renewable resources to the energy portfolio across the world has been steadily increasing over the past few years [22]. IRES is described as a system that harnesses two or more forms of locally available renewable energy resources to supply energy in an efficient, cost-effective, and practical way, with the ultimate goal of amalgamating the advantages at the user end [34] [35]. The increasing level of uncertainties introduced by wind and solar energy, traditional deterministic decision making in the electric power industry is gradually shifting towards stochastic decision making which explicitly considers the uncertainty in the power output of RES generators [36] [37].

The integration of intermittent and non-dispatchable generators like wind and solar exhibit sub-hourly fluctuations. This requires optimization of resources at multiple timescales. Renewable energy resources are highly site-specific, stochastic in nature and are evenly distributed around the world with little or no costs. They are greatly dependent on the climatic conditions, geographical factors and seasons of the site under consideration [38]. The most widely used and easily available renewable resources as inputs to IRES are Biomass, Hydro, Solar, Wind and Geothermal. A substantial number of renewable integration studies have focused on optimization requirements of power system with high renewable penetration such as wind [39] natural gas [31], and photovoltaic (PV) [40].

Azza A.Eldesouky (2013) [41] Presents a particle swarm optimization method to minimize the cost function and emissions of a given power system while satisfying all operational constraints considering both conventional and renewable generating units. This paper took advantage of the Weibull probability density function to anticipate the variable and stochastic behaviors of wind speed and solar irradiance.

This dissertation intends to add more renewable energy conversion technologies and reduce conventional generating units.

Dinghuan Zhu, et al. (2014) [7] investigates decomposition methods in stochastic optimization to facilitate parallel computing for the Security Constrained Economic Dispatch (SCED) problem in power systems with renewable energy and storage devices. A modified WECC 9-bus test system is used to optimize operating cost and Optimize security level. A dual decomposition scheme based on optimality condition decomposition (OCD) is helpful to decompose a highly complex optimization problem.

Guoqing Li et al. (2016) [31] clearly articulates the advantages of the Security-Constrained Economic Dispatch for Integrated Natural gas and electricity systems using IEEE 30 Bus system to minimize production cost and maximize security level. GAMS, SNOPT optimization were utilized. This article helped this dissertation identify suitable and relevant optimization tool and indicated that Security-Constrained Economic Dispatch can address security issues.

Hasnae Bilil et al. (2014) [40] studied MO RELD- NSGA-II to optimize annualized cost and optimize renewable energy-load disparity of Belgium’s electricity transmission system. Multi-objective optimization of renewable energy penetration rate in power systems that specially focus on wind and solar PV is discussed. This dissertation takes advantage of the methodologies of taking penetration rates and applying genetic algorithms.

Kiran Teeparthi et el. (2017) [9] uses IEEE 30 bus and practical Indian 75 Bus test systems to minimize total production cost, minimize active power loss and maximize the security level of a power system with wind and thermal generating units. Power grids are transitioning towards smart and green grids. This paper’s methodology on using the practical Indian 75 Bus test system helps this dissertation develop methods of adopting it for Ethiopian power systems.

Saoussen Brini et al. (2009) [42] Economic Dispatch for Power System included Wind and Solar Thermal energy using IEEE 24 Bus test system to minimize deviation of transactions and minimize the operating cost of generation is studied. The problem addressed in this paper is the Economic Environmental Dispatching (EED) of hybrid power system including wind and solar thermal energies. This dissertation extends the hybrid system in this study by including other RES and make it IRES.

Sundus Shafiq (2018) [43] conducted a research entitled “An Approach towards efficient energy Distribution and Power Flow Management in Smart Grid using Various Meta-Heuristic Techniques” to optimize operating cost and optimize security level of IEEE 39 Bus system. Detailed explanations and elaborations of smart grid architecture, energy management approaches and optimization method are provided.

TABLE 1-1. PAPERS ON SCEDOF POWER SYSTEM WITH IRES

Ref.	Optimization Type/ tools	Objective function	Case study / Test system
[6]	MOSCOPF, HPSO-APO	Minimize active power loss and Maximize security level	IEEE 30 bus system Indian 75 Bus system
[7]	MOSCED,	Minimize deviation of transactions and Minimize operating cost of generation	IEEE 24 Bus system
[8]	SCED, GAMS, SNOPT	Minimize production cost and Maximize security level	IEEE 30 Bus system
[9]	MO SCED- EA,HOMER, MATLAB	Minimize cost of electricity Maximize utilization	IEEE test systems
[10]	MO RELD- (NSGA-II)	Optimize annualized cost	Belgium's electricity transmission system
[11]	MOSMPC SCED-OCD	Optimize operating cost and Optimize security level	Modified WECC 9-bus test system
[12]	SCED-IRESIO	Optimize operating cost and Optimize security level	IEEE 39 Bus system

2.2.6. SCED with post contingency corrective actions

With the increasing penetration of renewable generation in modern power systems, uncertainty has become one of the biggest challenges in power system operation [43]. Due to the massive integration of variable generation, system operators have been enduring considerable unplanned disturbances and outages [18] [44]. SCED with post contingency corrective actions is proposed for avoiding these disturbances at the post contingency state [23] [45].

SCED is commonly classified into two different types: preventive SCED (PSCED) and corrective SCED (CSCED). In post contingency states, PSCED does not consider reprogramming of control variables. On the other hand, CSCED can correct rescheduling within a certain limit to satisfy more contingency scenarios. To deal with the contingencies, recent advances have been made along two major avenues: (i). Contingency Filtering (CF) techniques [31] [37], to effectively reduce the problem size and (ii). Decomposition and parallel algorithms [46] [47] to obtain approximate global solutions efficiently. Approaches of increasing the security level of a power system in connection with a post contingency state have been reported.

Hirth Lion et al. (2014) [4] studied the Polish 2383-bus system to minimize the base-case ED cost, computing scalable managing infeasible contingencies and maximize security level using SC-SCED, CPLEX ,API optimization tools. It clearly indicated the economics of wind & solar variability. It also shows how the variability of wind and solar power affect their marginal value, optimal deployment, and integration.

JunHua Zhao et al. (2012) [44] an economic dispatch model that considers the uncertainties of plug-in electric vehicles (PEVs) and wind generators, is developed. A simulation-based approach is employed to investigate the probability distributions of the charge/discharge behaviors of PEVs. A practical IEEE 300 Bus system, a Chinese power system is utilized to minimize operating cost and maximize security level.

Maria Vrakopoulou (2013) [18] studied optimal decision making for secure and economic operation of power systems under uncertainty to minimize operating cost of IEEE 30 Bus system, Finish Transmission system using MOSCELD- MATLAB and CPLEX optimization tools. In this dissertation, ways of anticipating uncertainty of the Finish Transmission system is clearly articulated. The methodologies and organizational structure of this dissertation will be used to develop our dissertation.

Michael Ferris (2014) [48] clearly articulated modeling and computation of Security-constrained Economic Dispatch with multi-stage rescheduling power generation, transmission and distribution. Determined generators' output to reliably meet the load using IEEE 30, 57 and 118 Bus systems to maximize security level. This paper helps this dissertation to identify feasible post contingency operating points.

TABLE 1-2. PAPERS ON SCEDWITH POST CONTINGENCY CORRECTIVE ACTIONS

Ref.	Optimization Type/ tools	Objective function	Case study / Test system
[13]	SCED-SDP ACF-SDP	Maximize security level(Identify feasible post contingency operating point)	IEEE 30, 57 and 118 Bus systems
[14]	MRSCED- IBD, GAMS, CPLEX	Maximize security level and Minimize operating cost	IEEE 30, 57 and 118 Bus systems
[15]	MOSCELD- MATLAB and CPLEX	Minimize operating cost	IEEE 30 Bus system, Finish Grid
[16]	CSCOPF, MCSCOP, ICF	Minimize operating cost Maximize security level	IEEE 300 Bus, Zhejiang543-bus grid
[17]	SC-SCED, CPLEX ,API	minimize ED cost, computing Scalable Managing infeasible contingencies	Polish 2383-bus system

2.2.7. Artificial intelligence based SCED

For the last two decades, researchers have been looking for an optimization method with better global optimum searching performance and fast convergence. This led to the understanding of heuristic, or random search, optimization methods. Many of these techniques have been applied to SCED problems, including Ant Colony Optimization (ACO), Artificial Neural Networks (ANN), Bacterial Foraging Algorithms (BFA), Chaos Optimization Algorithms (COA), various Evolutionary Algorithms (EAs), and Tabu Search (TS) [33] [43] [49] [50]. Substantial authors have presented efficient algorithms in the applications of linear and nonlinear programming methods.

A wide variety of intelligent techniques have been applied in solving the ELD problems like Genetic Algorithm (GA), Particle Swarm Optimization (PSO)and other learning/ adapting based methods [51] [52] [53] [54] [55][41] [56] [57]. Selected papers on artificial intelligence based SCED are clearly articulated in the forthcoming paragraphs.

Irina Ciornei (2011) [17] used the Cyprus power system to minimize the cost of generation and maximize security level using the MO SCED- HGAAPI solution method. The algorithm proposed is called GAAPI and is a hybridization between two optimization techniques: a special class of ant colony optimization for continuous domains entitled API and genetic algorithms.

Hasnae Bilil et al. (2014) [40] studied the MO RELD- NSGA-II to optimize annualized cost and optimize renewable energy-load disparity of Belgium’s electricity transmission system. Multi-objective Optimization of Renewable Energy Penetration Rate in Power Systems that specially focus on wind and solar PV is discussed. This study takes advantage of the methodologies of taking penetration rates and applying genetic algorithms.

M. Murali et al. (2013) [58] used IEEE 14 Bus, Indian 75 Bus system and New England 39 Bus test systems to minimize bus LMP and minimize total fuel cost using LMP, and SCED- GA solution methods. This paper proposed GA based SCED for LMP calculation that is proved to be very simple, reliable and efficient in all the studied cases. Genetic algorithm formulations mentioned in this paper are used as inputs to the proposed solution methods of this dissertation.

TABLE 1-3. PAPERS ON ARTIFICIAL INTELLIGENCE BASED SCED

Ref.	Optimization Type/ tools	Objective function	Case study / Test system
[18]	MOSCED- LP, QP, NFP, NCLFP, GA	Minimize cost of generation, Minimize cost of power loss and Maximize security level	IEEE 5, 30 Bus systems
[19]	LMP SCED- GA	Minimize bus LMP and Minimize total fuel cost	IEEE 14 Bus system, Indian 75 Bus system New England 39 Bus system
[20]	ELD, CSO	Minimize total fuel cost	3-Generating Units, 6 Generating Units
[21]	PED, IIA MU	Minimize total operating cost	5- Unit system 15-Unit system
[10]	MO RELD- (NSGA-II)	Optimize annualized cost Optimize renewable energy – load disparity	Belgium's electricity transmission system
[22]	MO SCED- HGAAPI	Minimize cost of generation and Maximize security level	Cyprus Power System

2.3. SCED Research Directions: State of the Art

As can be deduced from the comparison tables and figures 2-2 and 2-3 of the literature review, the papers presented are closely related to SCED of IRES. It is indicated that there needs to be provided with enough state-of -the -art review and survey of papers of optimization methods of SCED of IRES. The general theme of this literature review is to articulate research gaps that support the problem statement.

TABLE 1-4. PAPERS ON SCED RESEARCH DIRECTIONS STATE OF THE ART

References	Optimization Type	Objective function	Case study
[18]	MOSCED-LP, QP, NFP, NCLFP, GA	Minimize cost of generation & power loss and Maximize security level	IEEE 5, 30 Bus systems
[11]	MOSMPC SCED-OCD	Optimize operating cost and Optimize security level	Modified WECC 9-bus test system
[6]	MOSCOPF, HPSO-APO	Minimize production cost, Minimize active power loss	IEEE 30 bus system an Practical Indian 75 Bus
[7]	MOSCED	Minimize deviation of transactions and Minimize operating cost of generation	IEEE 24 Bus system
[8]	SCED, GAMS, SNOPT	Minimize production cost and Maximize security level	IEEE 30 Bus system
[9]	EA,HOMER, MATLAB	Maximize utilization of resources	IEEE test systems
[10]	MO RELD- (NSGA-II)	Optimize renewable energy load disparity	Belgium's electricity transmission system
[12]	SCED-IRESIO	Optimize operating cost and Optimize security level	IEEE 39 Bus system
[13]	SCED-SDP ACF-SDP	Maximize security level	IEEE 30, 57 and 118 Bus systems
[14]	MRSCED- IBD, GAMS, CPLEX	Maximize security level and Minimize operating cost	IEEE 30, 57 and 118 Bus systems
[15]	MATLAB and CPLEX	Minimize operating cost	IEEE 30 Bus system, Finish TSO
[16]	CSCOPF, MCSCOP, ICF	Minimize operating cost Maximize security level	IEEE 300 Bus system, Chinese 543-bus grid
[17]	SC-SCED, CPLEX ,API	Minimize ED cost & maximize security level	Polish 2383-bus system
[19]	LMP SCED- GA	Minimize bus LMP and Minimize total fuel cost	Indian 75 Bus system New England 39 Bus
[20]	ELD, CSO	Minimize total fuel cost	3-Generating Units, 6 Generating Units
[21]	PED, IIA MU	Minimize total operating cost	5- Unit system 15-Unit system
[22]	MO SCED- HGAAPI	Minimize cost of generation and Maximize security level	Cyprus Power System

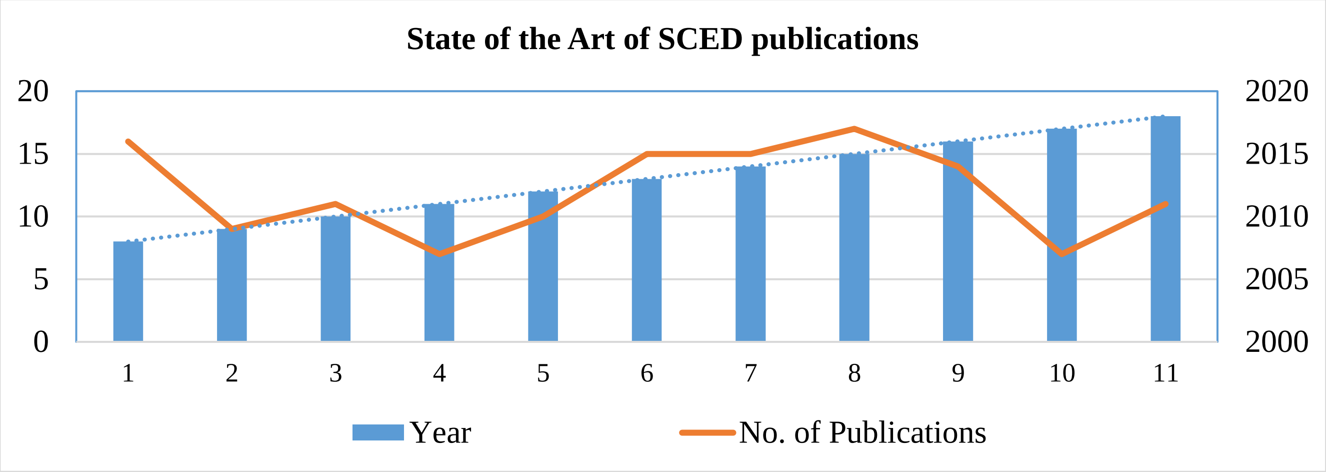


Figure 2-2. State of the Art of SCED publications

In one decade, 82 papers of SCED for power systems with renewable penetration have been reported. It has been tried to include as many descriptions of the contents as possible in order to show the important and unique aspects of each paper. The attempt is not directed at evaluating and comparing relative performances of the existing algorithms but at presenting a clear picture of the state-of-the-art of SCED to identify research gaps and future developments.

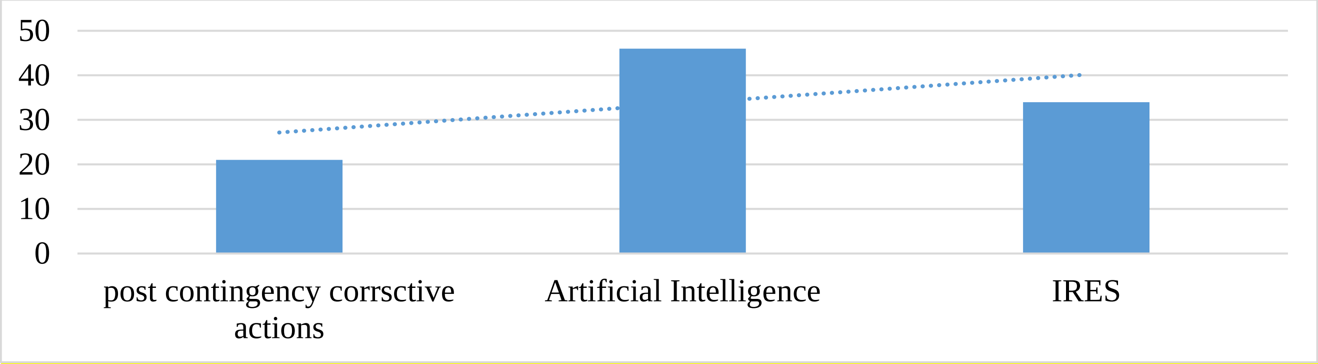


Figure 2-3. No. of publications by Area of interest

As it can be seen from the above figure, there is a growing interest on SCED with IRES and artificial intelligence-based SCED. It is believed that this trend will continue as long as faster computers keep evolving and more efficient optimization algorithms are used. It is obvious from this survey that, SCED of a power system with IRES and artificial intelligence based SCED are important areas of future research. Considering post-disturbance corrective actions, formulating an intelligent searching algorithm with fast convergence, and taking into account the intermittency of all recently innovated renewable energy sources are some of the future research areas of SCED.

Generally, underlining the strengths, this literature review paves a way to articulate the following research gaps:

- A comprehensive survey on recent trends and state of the art of SCED applied for renewable energy sources was not available. There is a lack of literature and research on SCED for renewable energy systems.
- SCED for a power system comprising more than three types of renewable energy conversion technologies was never formulated before. This gap is leading researchers to understand economic dispatch as only economic calculation instead of understanding it as a power operation and planning task.
- There is no concrete evidence that claims SCED of IRES with credible contingencies that show the effects of high penetration of power system by intermittent renewable energy systems.
- The prospects and challenges of computational intelligence based Security Constrained Economic Dispatch (SCED) for Ethiopian Renewable Energy Systems (ERES), which is a nonexistent practice in the Ethiopian generation plan demands both intensive and extensive research.
- Hybrid GA-HNN optimization method was not applied for solving the SCED problem before and there is no clear indication on how the Ethiopian power system network is economically dispatched.
- Hybrid GA-HNN optimization method based SCED was not used for Ethiopian Renewable Energy systems before and there is no clear indication on how the Ethiopian power system network is economically dispatched in connection with recursive blackouts and power service interruptions.

2.4. Renewable Energy Systems

Apart from having a lower carbon footprint, RESs have another significant advantage compared to the traditional generation: their modularity. This means that they can be placed near or at the place where electricity is consumed, reducing transmission losses [1]. However, the wide adoption of solar and wind energy still faces major challenges. Firstly, both wind and solar power are non-dispatchable: power generation from these sources cannot be adjusted at will, even if it is necessary to do so. Secondly, although wind and solar energy are already cost-competitive in places with some of the highest solar and wind potentials, solar panels and wind turbines remain a costly investment in many parts of the world [2]. Moreover, more than 90% of the energy demand growth until 2035 will come from developing countries [3], whose purchasing power hinders the uptake of renewable energy.

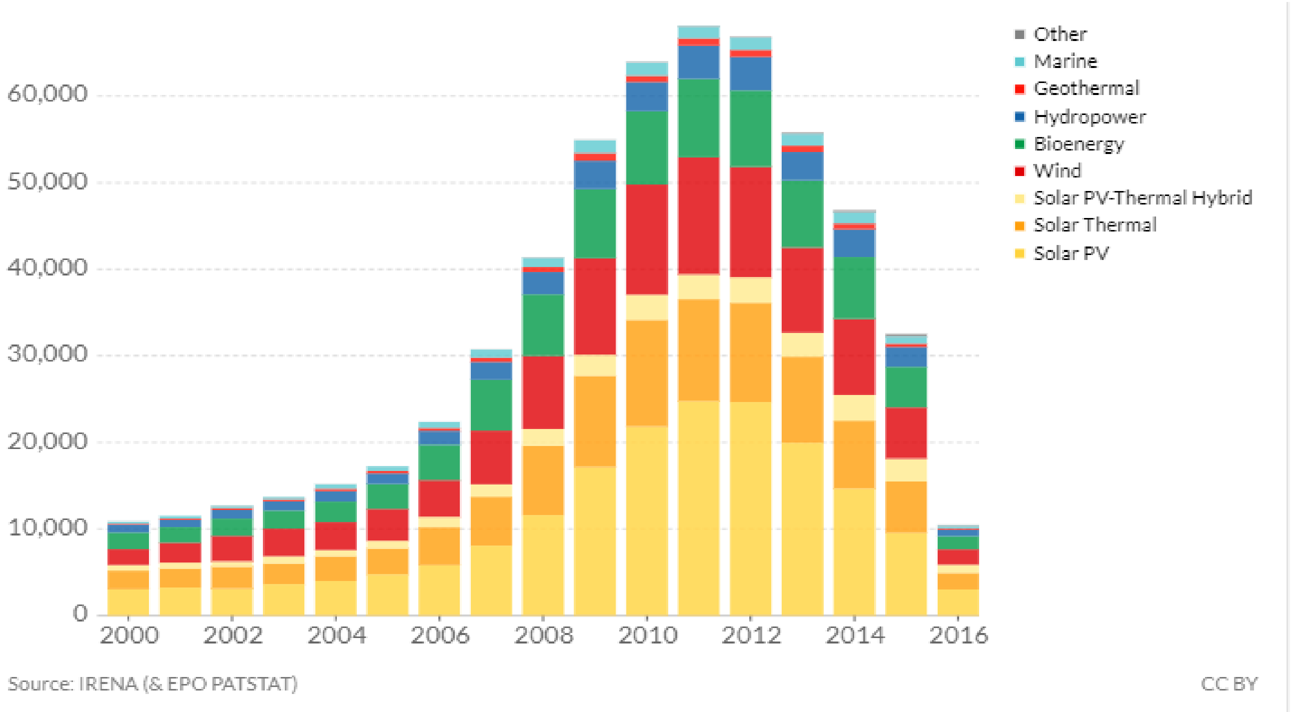


Figure 2-4. IRENA's global data showing historical trends of rapidly growing renewable generation installed capacity (2000-2016) [59]

The world economy is growing to meet the development aspirations of countries around the globe. This, in turn, will lead to an increase in energy demand, even if vigorous efforts are made to increase the efficiency of energy use and energy conservation. The interest in the new and environment friendly energy system is growing worldwide. Solar and wind energy systems are taking the biggest share from this current trend. Renewable energy resources can meet most of the growing demand, provided suitable approaches and requisite support are brought to bear.

The potential of renewable energy sources is vast and they can meet the world's energy demand multiple times. Tens of gigawatts of wind, hydropower, geothermal, biomass waste to energy and solar photovoltaic capacity are installed worldwide every year into the renewable energy market [59]. Intensive studies are being conducted on alternative energy sources including the newly emerging Nanotube technologies [60], electric vehicles [44], smart roads [61] and sustainable road pavement based green energy source [62]

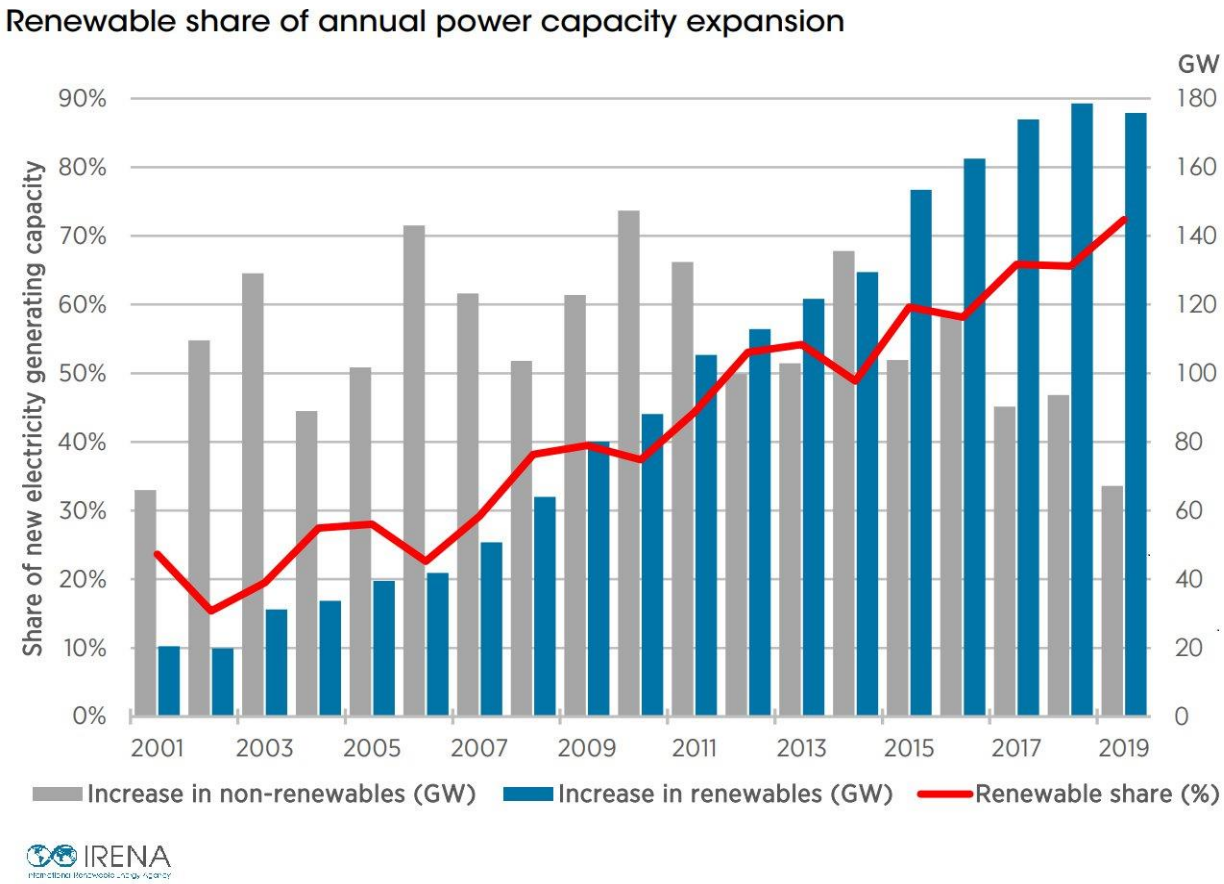


Figure 2-5. Renewable share of annual power capacity expansion (2001-2019) [59]

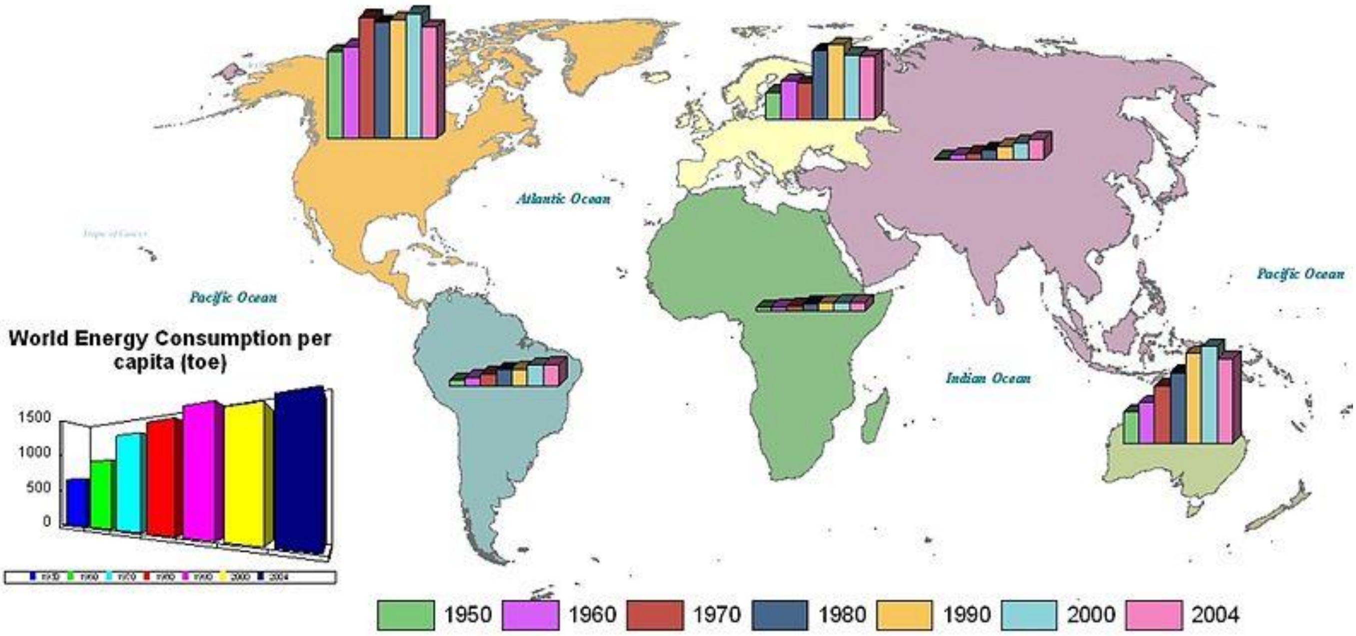


Figure 2-6. History of world energy consumption per capita (1960-2004) [63]

Modern-day distributed power generation mainly depends on renewable sources due to their advantage of being infinite and environment friendly subsequently reducing dependence on fuel, coal and oil. However, they pose economic and technical challenges to a secure and reliable power system operation. They are mostly less controllable since their primary energy sources cannot be controlled. Therefore, integrating renewable energy systems into a power system poses technical and economic challenges. Making a transition to a renewables-intensive energy economy would provide environmental and other advantages, which cannot be measured in standard economic terms.

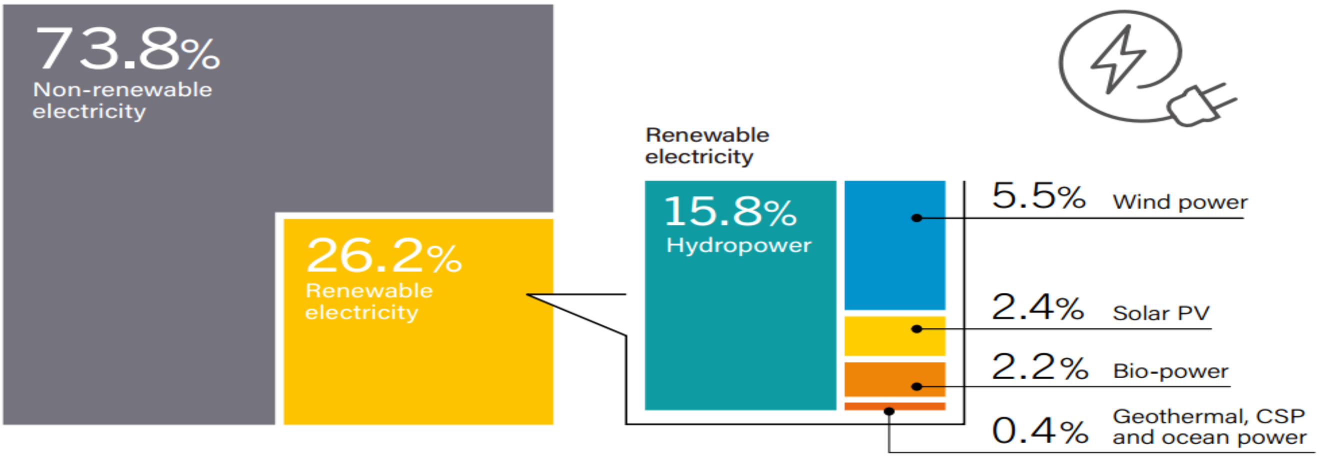


Figure 2-7. Global generation share until 2010 [64]

2.4.1. Solar Energy

Solar energy can be converted to useful energy forms through a variety of demonstrated technologies. One-way to exploit this energy is by using solar thermal technologies. Heat collected can be used for space heating or can be stored in a thermal medium such as water or molten salt. The need for electricity-generating capacity can be reduced when solar energy replaces electricity in such applications. Another way of using solar energy is through solar photovoltaic (PV) technologies. Solar photovoltaic technologies directly absorb incident photons without complete conversion to heat. As far as available solar technologies are concerned, solar photovoltaic (PV) is the most promising.

The major issue facing PV technology is cost. The cost of PV is reducing and its efficiency has improved. Solar PV is becoming more popular because of its high modularity, no requirement for additional resources, and low maintenance. The cost of manufacturing and installing solar PV systems has decreased by about 20% for every doubling of installed capacity. Ethiopia receives solar irradiation of 5-7 kWh/m^2, which is a great potential for the use of solar energy. The average solar radiation is around 5.2 kWh/m^2/day. With this potential, solar PV electrification is the most appropriate technological option for electrifying rural areas of the country.

2.4.2. Wind Energy

In simple terms, the wind is moving air. It has been harnessed since ancient times. Ancient Egyptians utilized wind to sail ships on the Nile River as early as 5000 B.C. Later, people invented windmills to grind wheat and other grains. The kinetic energy from continuously blowing wind can be converted using wind into mechanical energy and then into electrical energy. Electricity generated by wind turbines can be fed to the central grid or be locally consumed using small stand-alone wind turbines.

The utilization of wind energy helps to achieve a healthy ecosystem by significant reductions of CO2 emitted to the atmosphere. Wind speed at any particular wind farm location can be described as a stochastic process. This process exhibits spatial correlation with processes describing wind speeds at other geographically separated wind farm locations. According to the Ethiopian National Meteorological Services Agency (NMSA), Ethiopia has a wind resource with velocities ranging from 7 to 9 m/s. Its wind energy potential is approximately 10,000 MW [65].

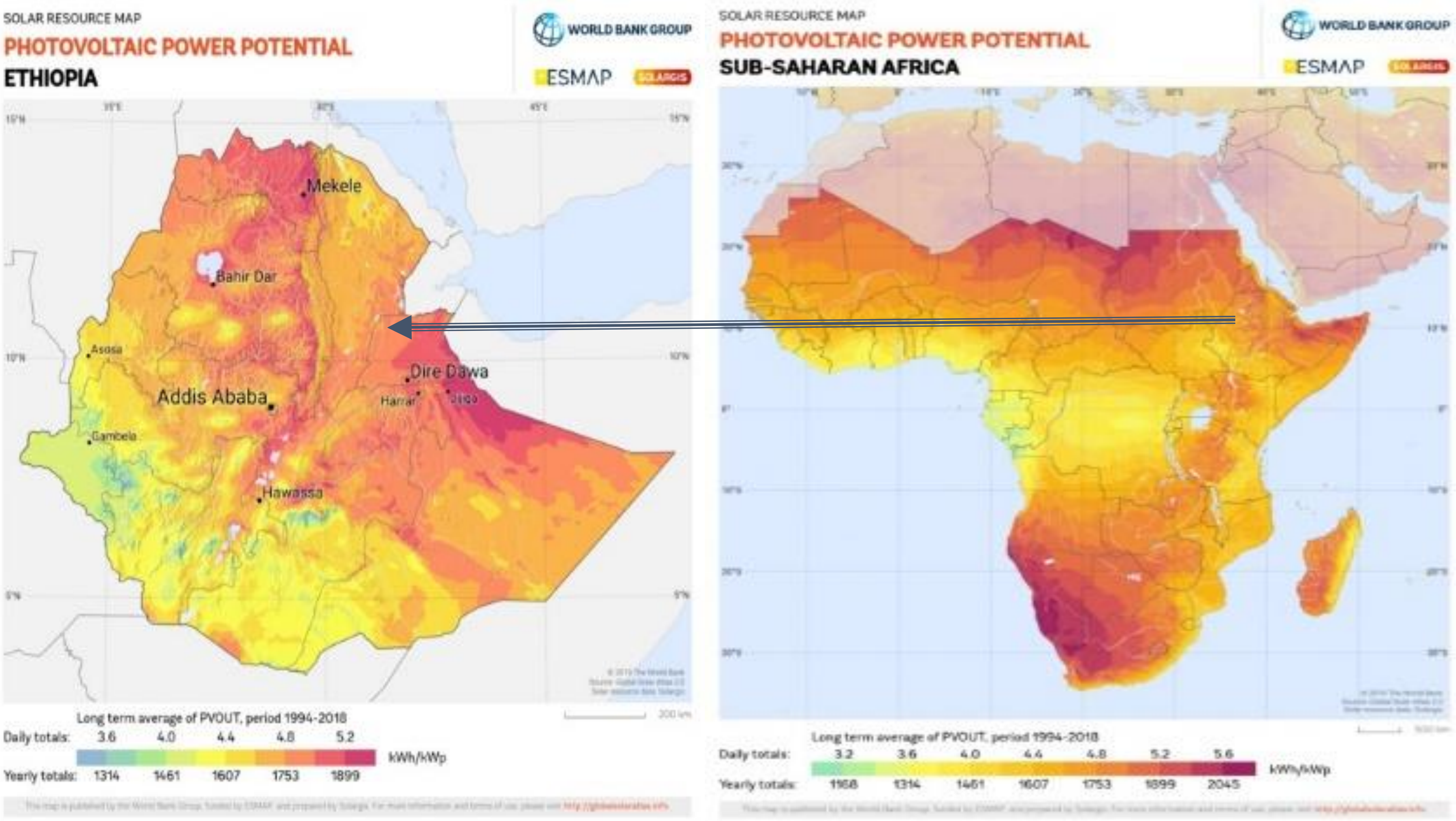


Figure 2-8. Solar energy potential map

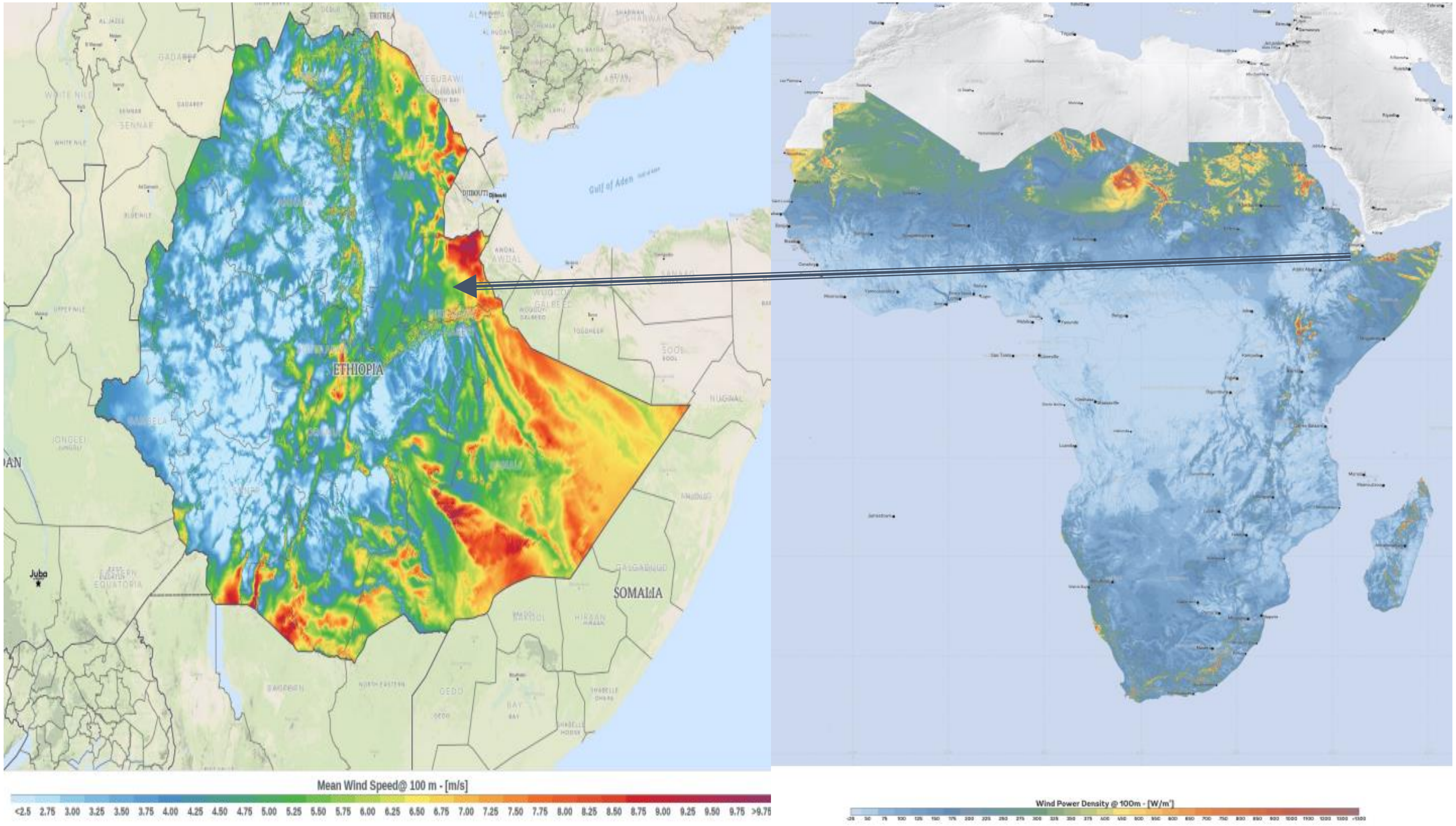


Figure 2-9. Wind energy potential map

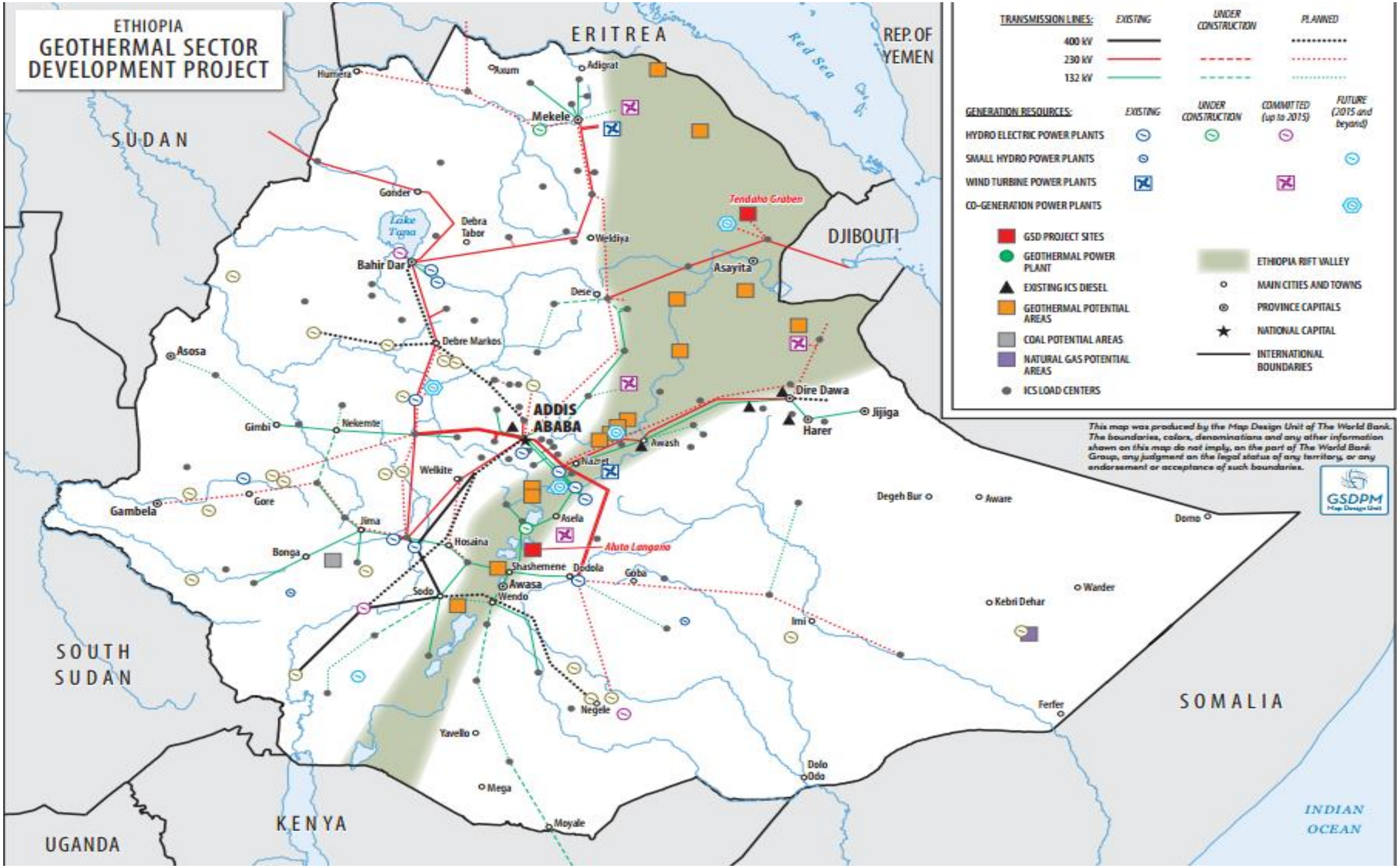
1

2.4.3. Geothermal Energy

The geothermal energy of the Earth's crust emanates from the original formation of the planet and from the radioactive decay of materials [66].There are different geothermal technologies for distinct levels of maturity. Technologies for direct applications like district heating, geothermal heat pumps, greenhouses, and other applications are common and can be considered mature. Geothermal power is economical, reliable, sustainable, and environmentally benign. Through proper reservoir management, the rate of energy extraction can be often balanced [67].

Geothermal power plants produce electricity consistently, running 24 hours per day/7 days per week, regardless of weather conditions, thus can be used as base loads. Modern closed-loop geothermal power plants have no greenhouse gasses emissions. GHG emissions are four times lower than solar PV: and six to 20 times lower than natural gas. Geothermal power plants use smaller land per GWh than coal, wind,or solar PV with center station [68].

Ethiopia's geothermal resources are estimated to be 5 GW of which 700 MW are suitable for electrical power generation [69]. Ethiopian geothermal resources are primarily located in the Rift Valley area, where temperatures of 50-300°C prevail in a depth of 1,300-2,500 m. One 7.3 MW geothermal power plant has been commissioned so far, which started operating in 1998/1999 but was shut down due to lacking technical maintenance in 2002. It has started operation again, but only at a reduced generation rate. Exploration of geothermal resources is still ongoing [69] [70] [71].


ETHIOPIA
GEOTHERMAL SECTOR DEVELOPMENT PROJECT
ERITREA
SUDAN
REP. OF YEMEN
Red Sea
DJIBOUTI
SOUTH SUDAN
SOMALIA
KENYA
UGANDA
INDIAN OCEAN
ADDIS ABABA
Humera
Axum
Adigrat
Mekele
Gonder
Lake Tana
Debra Tabor
Bahir Dar
Weldiya
Tendaho Graben
Asayita
Dese
Debre Markos
Asosa
Dire Dawa
Jijiga
Harer
Awash
Nazret
Gimbi
Nekemte
Welkite
Gambela
Gore
Jima
Bonga
Hosaina
Asela
Aluto Langano
Shashemene
Dodola
Goba
Awasa
Wendo
Sodo
Degeh Bur
Aware
Domo
Warder
Kebri Dehar
Imi
Negele
Yavello
Mega
Moyale
Dolo Odo
Ferfer
TRANSMISSION LINES:
EXISTING
UNDER CONSTRUCTION
PLANNED
400 kV
230 kV
132 kV
GENERATION RESOURCES:
EXISTING
UNDER CONSTRUCTION
COMMITTED (up to 2015)
FUTURE (2015 and beyond)
HYDRO ELECTRIC POWER PLANTS
SMALL HYDRO POWER PLANTS
WIND TURBINE POWER PLANTS
CO-GENERATION POWER PLANTS
GSD PROJECT SITES
GEOTHERMAL POWER PLANT
EXISTING ICS DIESEL
GEOTHERMAL POTENTIAL AREAS
COAL POTENTIAL AREAS
NATURAL GAS POTENTIAL AREAS
ICS LOAD CENTERS
ETHIOPIA RIFT VALLEY
MAIN CITIES AND TOWNS
PROVINCE CAPITALS
NATIONAL CAPITAL
INTERNATIONAL BOUNDARIES
This map was produced by the Map Design Unit of The World Bank. The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.
GSDPM
Map Design Unit

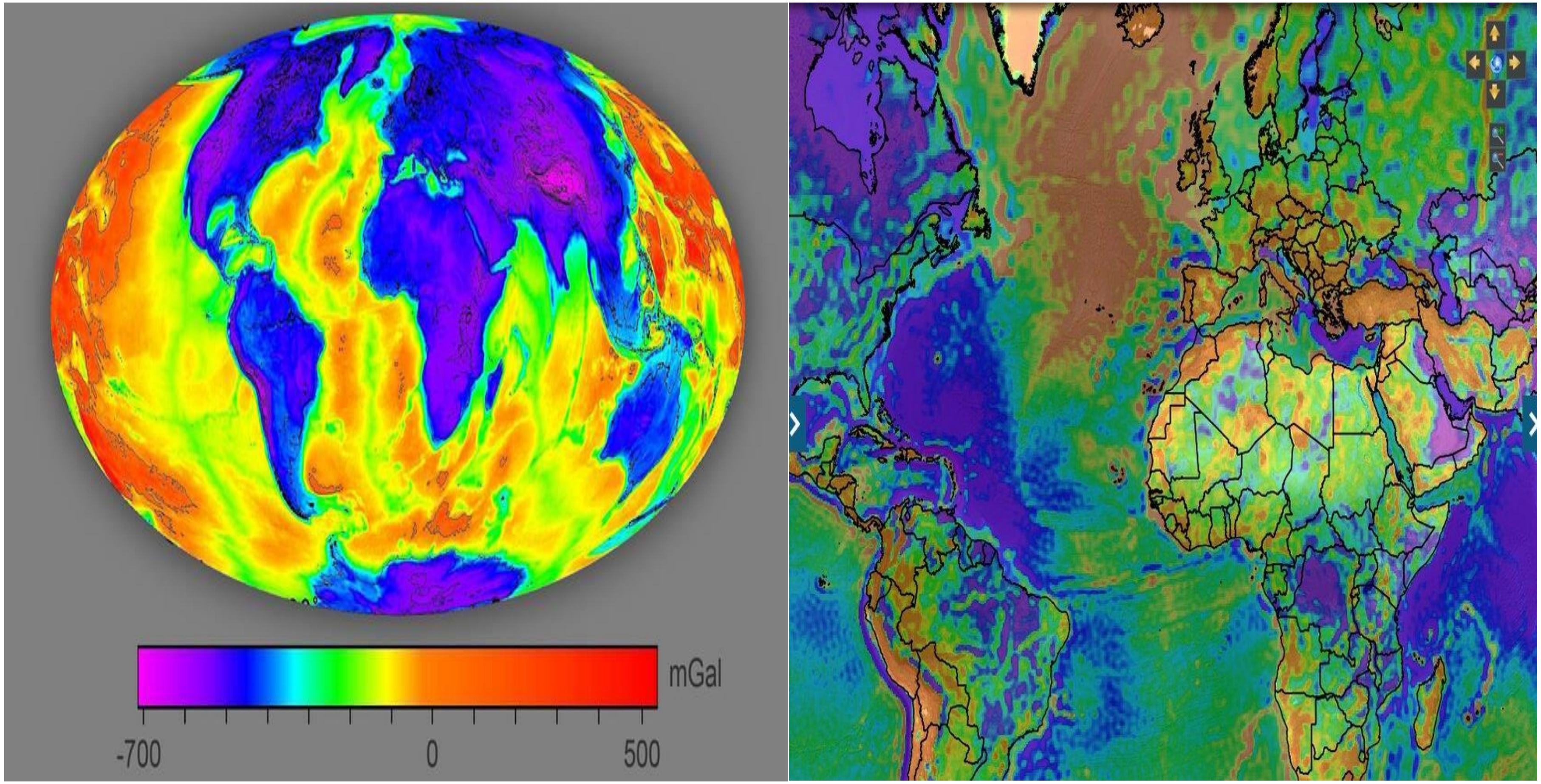
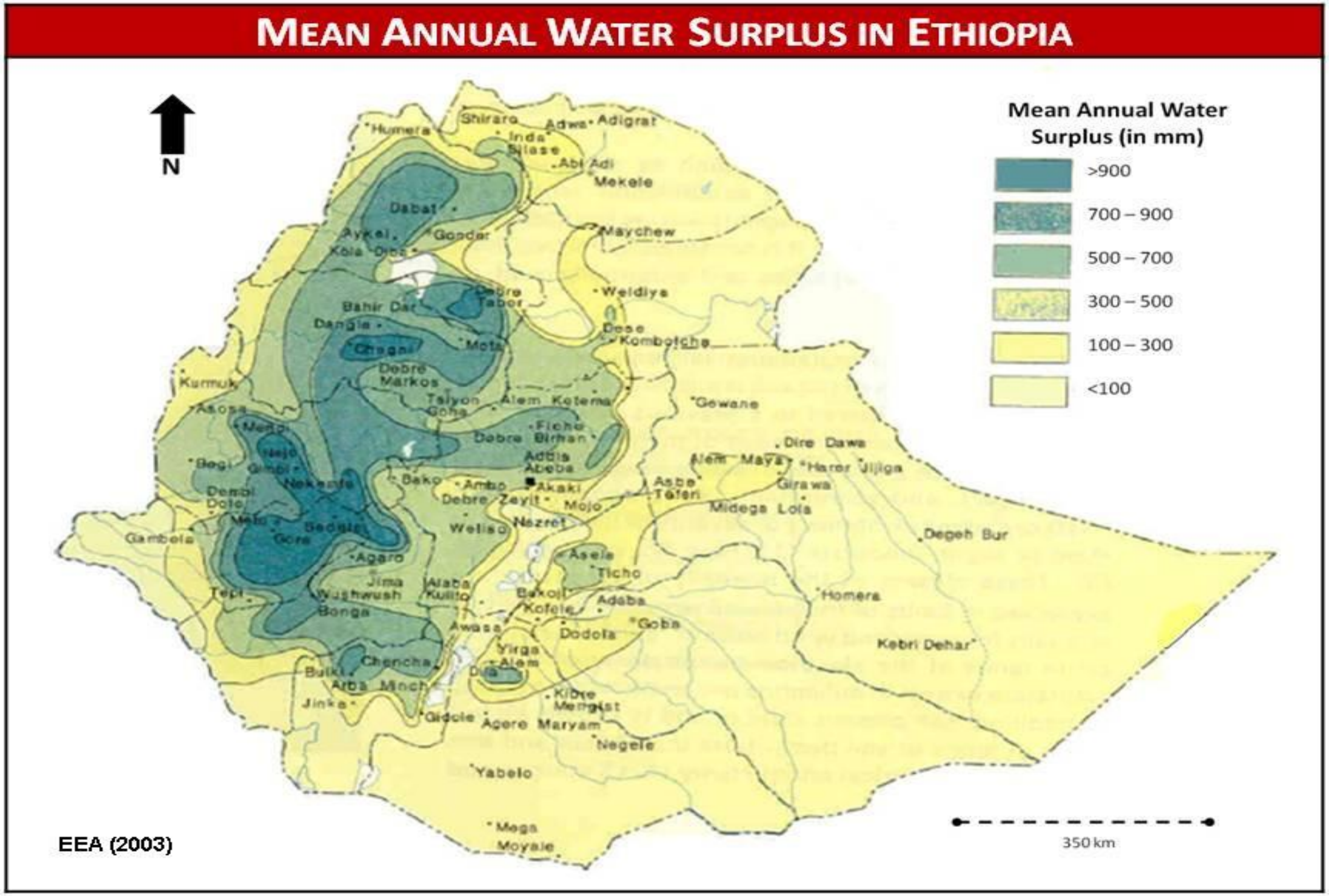


Figure 2-10. Geothermal energy potential map


MEAN ANNUAL WATER SURPLUS IN ETHIOPIA
N
Mean Annual Water Surplus (in mm)
>900
700 – 900
500 – 700
300 – 500
100 – 300
<100
Humera
Shiraro
Inda Silase
Adwa
Adigrat
Abi Adi
Mekele
Dabat
Gondar
Aykel
Kola Diba
Maychew
Bahir Dar
Debre Tabor
Weldiya
Dangila
Dese
Kombolcha
Chagni
Mota
Debre Markos
Kurmuk
Asosa
Tsiyon Goha
Alem Ketema
Gewane
Mendi
Fiche
Debre Birhan
Dire Dawa
Nejo
Gimbi
Begi
Addis Abeba
Alem Maya
Harar
Jijiga
Nekemte
Bako
Ambo
Akaki
Asbe Teferi
Girawa
Dembi Dolo
Debre Zeyit
Mojo
Midega Lola
Metu
Sedgela
Weliso
Nazret
Degeh Bur
Gambela
Gore
Agaro
Asela
Ticho
Jima
Alaba Kulito
Tepi
Wushwush
Bekoji
Homera
Bonga
Kofele
Adaba
Awasa
Goba
Dodola
Yirga Alem
Kebri Dehar
Chencha
Bulki
Dila
Arba Minch
Kibre Mengist
Jinka
Gidole
Agere Maryam
Negele
Yabelo
Mega
Moyale
EEA (2003)
350 km

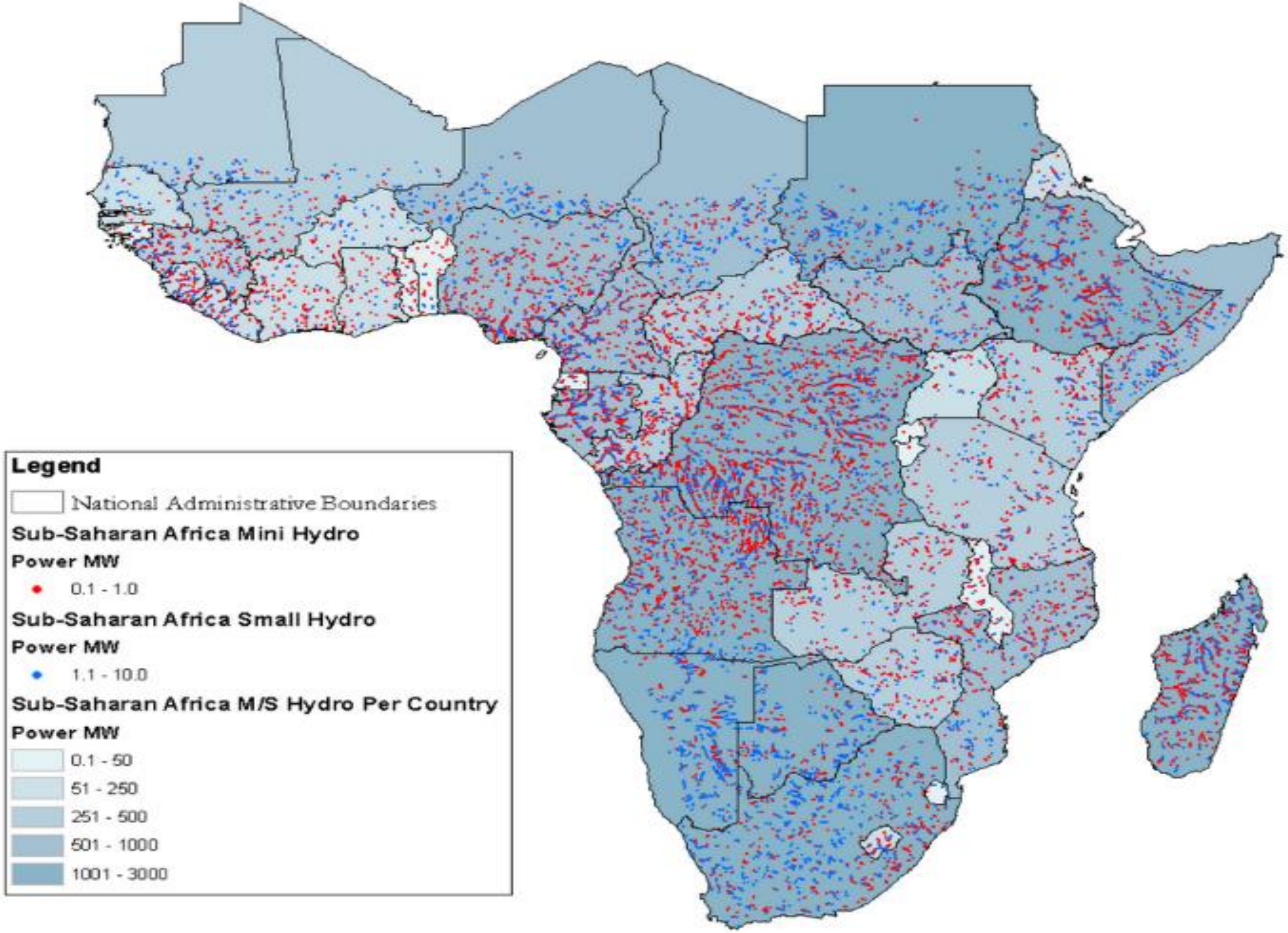


Figure 2-11. Hydropower energy potential map

2.4.4. Hydropower

Ethiopia's hydropower potential is approximately 45,000 MW and is the 2nd highest in Africa after DR. Congo. Approximately 30,000 MW is believed to be economically feasible, which is equivalent to an electricity generation of 162 TWh. The current production of 3.98 TWh thus equals to an extraction of only 2.5%. In general, Ethiopia’s topography is advantageous for hydropower generation projects. With 10 river basins (of which the Blue Nile, Omo and Wabi Shebelle, and Genale-Dawa are international rivers), hundreds of streams flowing into the major rivers dissecting the mountainous landscape in every direction; and each river basin covering massive catchment areas with adequate rainfall, Ethiopia is said to be the “Water Tower of Eastern Africa”[10].

2.4.5. Biomass Energy

Residues from forests, wood processing, and food crops are dominant in biomass energy. This technology can be utilized on a larger scale for generating electrical power. Worldwide, biomass provides basic energy requirements for rural households cooking and heating in developing countries. Biomass energy generation offers a promising solution to environmental challenges by reducing the emission of common GHGs. Several technologies exist for converting biomass into heat energy and electrical energy. Two widespread technologies are direct combustion and gasification. Direct combustion includes the oxidation of biomass resources with excess air to produce hot flue gases that in turn produce steam that is used to generate electricity.

2.5. Why renewable energy systems

a. **Renewable:** This implies that they do not exhaust over a lifetime, and there is a minimal possibility that they are not sustainable sources of energy. Sources of energy like oil, gas, and coal are considered limited resources, and there is a maximum possibility that they will run out in the future. Renewable energy can help developing countries escape from over-reliance on fossil fuels. Powerful winds, heat emanating from beneath the earth, sunshine and moving water can guarantee huge and steady energy needs to a country for a considerably long time [66].

b. **Environmental benefits:** According to recent studies, the transition to a low carbon energy generation can be achieved through a variety of technologies such as carbon capture and storage, nuclear energy, and renewable energies. Mitigating climate change requires a global transition towards energy systems with low or even negative GHG emissions. Renewable energy is considered clean energy since it doesn’t cause grave environmental pollution, and it has minimum carbon and greenhouse emission. Fossil fuels emit high levels of GHG and carbon dioxide, which contribute to global warming, climate change, and air quality degradation. The use of renewables dramatically decreases the dependence on fossil fuel as a source of energy, hence, cutting back on air pollution [72] [73].

c. **Modularity benefits:** Renewable energy systems are understood to be largely site-specific. Renewable energy systems can be installed close to the demand, given their availability. They are scalable, meaning they can have different sizes based on their applications. They can also be portable and applicable for peaking demand. This aspect of renewable energy systems reduces transmission line costs.

d. **Economic benefits:** Future energy systems will likely electrify the globe. However, some applications in the transportation and industry will require liquid or gaseous fuels, as the costs of fully electrifying these applications are immensely expensive. By covering these costs, renewables can enhance the economy of a nation accordingly.

e. **Low maintenance and operation costs:** Renewable energy technologies require less overall maintenance than traditional generators that use traditional fuel sources. These renewable energy generating technology like solar panels and wind turbines either have few or no moving parts. Above all, they do not rely on flammable, combustible fuel sources to operate, which makes the operating costs lower too.

f. **Recycling benefits:** Biomass energy has this particular benefit that more than any other form of renewables. Biomass consumes used organic products such as used vegetable oil, corn and soybean byproducts, or even algae to generate energy. At the same time, it reduces the waste that goes into landfills, also reducing the amount of overall carbon that goes into the atmosphere.

2.6. Current challenges with renewables in electricity markets

While renewable resources have positive environmental and energy security attributes, their integration into energy networks, especially in large-scale power grids, pose several technological and operational challenges.

1. ***Intermittency***: Wind and solar energy fall under the class of variable generators because of their inherent variability. This variation is not only high in magnitude but also exhibits sub-hourly fluctuations in generation levels that make it challenging to predict.
2. ***Non-dispatch ability:*** Intermittent energy has one more characteristic that is different from conventional energy. Conventional energy is a capacity resource, which can be available on-demand, particularly to meet system peak loads. Only a fraction of total wind or solar capacity has a high probability of running consistently.
3. ***Power imbalance:*** There is also a temporal mismatch between the load and availability of these

resources. This along with intermittency mandates newer ways for power system planning and operation task.

4. *Challenges in electricity markets*

In current electricity markets, there are different market products aiming at minimizing the generation dispatch and the reserve costs, while satisfying the network constraints. The energy market determines the optimal generation dispatch. The transmission market considers network constraints and determines changes in the generation dispatch to ensure network security. However, there are also security related challenges in connection to the variability of renewable generation.

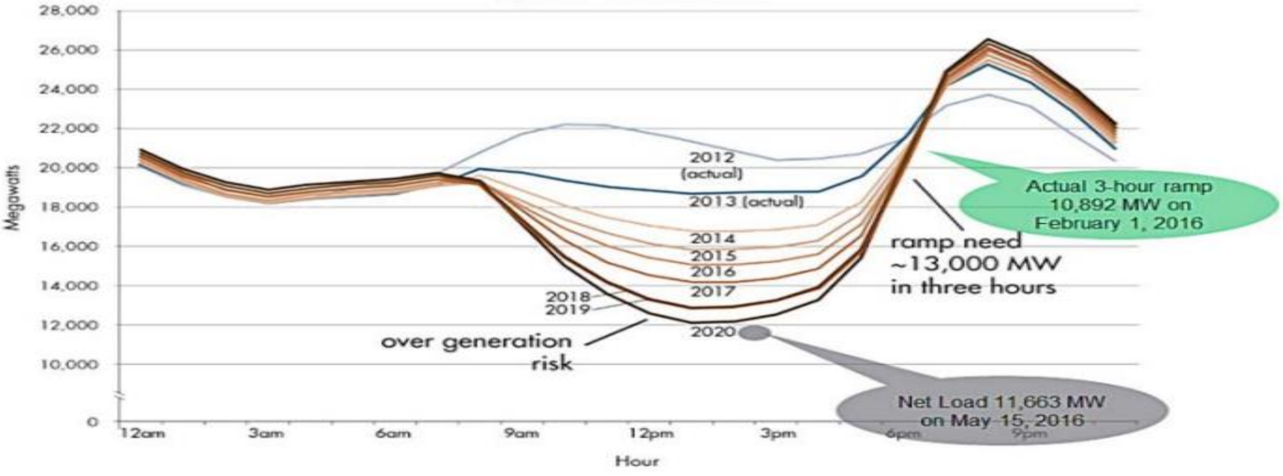


Figure 2-12. Solar generation challenge, the “Duck curve”

This variability and intermittency have a significant effect on power dispatch and electricity markets when renewables are deployed at a large scale. Currently, wind and solar generation supply only a small share of electricity; they are expected to play a larger role in the future [74]. Accordingly,

- Renewable generation is variable. This is because it is based on weather conditions and cannot be rescheduled like the output of dispatchable power plants. Due to renewable generation not coping up with the load, and electricity storage is costly, this variability is costly.
- Renewable generation is uncertain. Electricity trading takes place, production decisions are made, and power plants are committed the day before delivery. Deviations between forecasted renewable generation and actual production need to be balanced on short notice, which is costly.
- Renewable generation is location-specific, i.e. it is difficult to transport the primary energy mover like fossil or nuclear fuels. As a result, electricity transmission is costly.

The variable operating cost of electric power generators is a key factor in determining which generating unit of a power grid operates or dispatches to meet the electricity demand. Other things being equal, generating units with rock bottom operating costs are generally called upon first, and generating units with higher operating costs are brought online sequentially as per the electricity demand.

This particular dispatch order is often described by an electricity supply curve, also referred to as a dispatch curve, which represents the order during which generating units are dispatched to meet the electricity demand. Summary of renewable energy current challanges with respect to electricity markets and economic frameworks is presented in Figure 2-9.

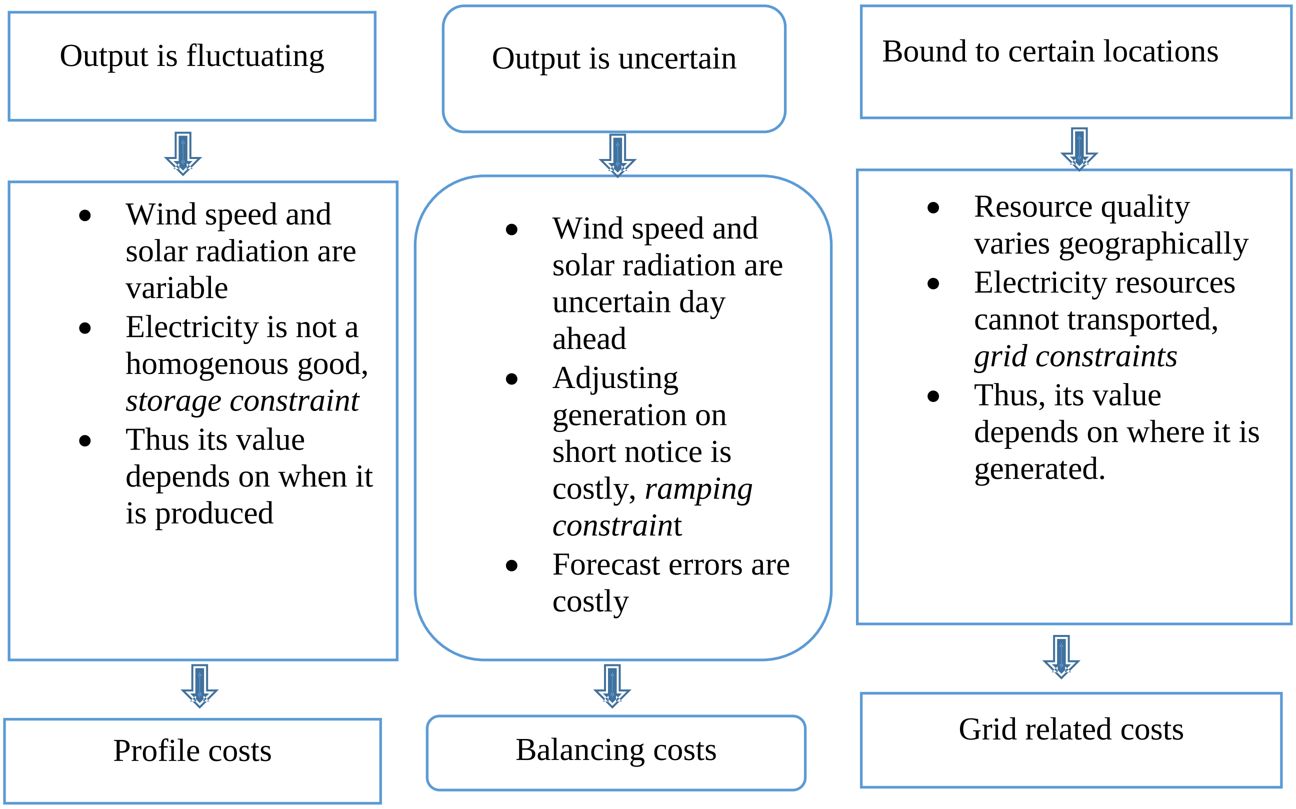


Figure 2-13. Summary of renewable energy current challenges with respect to the electricity market

2.7. Possible solutions: way-out

With the growing complexity and unpredictability of power grids, optimization of power economic dispatch is now more important than ever. It is imperative to overcome the challenges brought about by the rising deployment of intermittent renewable energy systems to capitalize on the opportunities and prospects they present. The following options can be the way outs of this challenging task in power system operation.

1. *Transmission and Operating Reserves*

Practically, operational variability arises from load fluctuations, generation output, unprecedented failures, and transmission equipment failures. Additional online or standby capacity, above the actual demand, has to be made available that can be called to assist if load increases or generation decreases. Likewise, an online generating capacity that can reduce supply or turn off is required if load decreases or generation increases. These are referred to as operating reserves. With the introduction of intermittent renewable resources, especially at high penetration, the importance of these operating reserves is increased tremendously.

2. *Storage*

The challenge posed due to non-dispatchability[§§] of the variable generation of renewable resources can also be overcome by deployment of energy storage devices in the network. Storage devices provide a means to avoid energy curtailment caused possibly by an increased renewable generation and failure to reduce the baseload generation with ramping constraints.

3. *Forecasting*

Forecasting allows operators to anticipate intermittent resource outputs in advance and hence aid in better planning. This can lead to variability reduction in energy networks. Many forecast systems employ the persistence method, which assumes that the current value will be the same at a future point in time. Others include statistical forecast models, which employ learning methods like Artificial Neural Networks. These compute forecasts and confidence intervals for the total aggregated wind power based only on historical data [37].

4. *Integrated renewable energy systems*

With the increasing entry of renewable energy systems into electricity markets, balancing, demand and supply became one of the most challenging power-system operation problems. Since renewables are intermittent and variable, their power outputs are stochastic and difficult to predict accurately. Moreover, renewable resources are intermittent and their inclusion in power systems may lead to instability of the power system network operations.

Hence, it is important to consider the variability of renewable resources so that the robustness of the system can be evaluated before integration can be deemed acceptable. Operating power systems in a secure way constitutes a critical task for ensuring a well-functioning society. However, security comes at the expense of additional investment and operational cost. The additional costs incurred to maintain a desired security level are expected to increase further due to the integration of Renewable Energy Sources (RES). In energy systems due to ramping response time of the conventional generators, their generation levels have to be set prior to the realization of renewable power. The actual dispatch of facilities gives rise to the recourse

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[§§] A non-dispatchable source of electricity generate electricity but cannot be turned on or off in order to meet societies fluctuating electricity needs. It is the opposite of dispatchable sources of electricity which are very flexible, being able to change their output fairly quickly in order to meet electricity demands. Non-dispatchable electricity sources are often highly intermittent, which means that they are not continuously available due to factors that cannot be controlled. There are many different types of non-dispatchable sources like tidal power and wave power. However, two main types that contribute noticeably to the electrical grid: Solar power and wind power.

problem, which is solved after the power output is known. Corresponding possible solution to the current challenges are listed below.

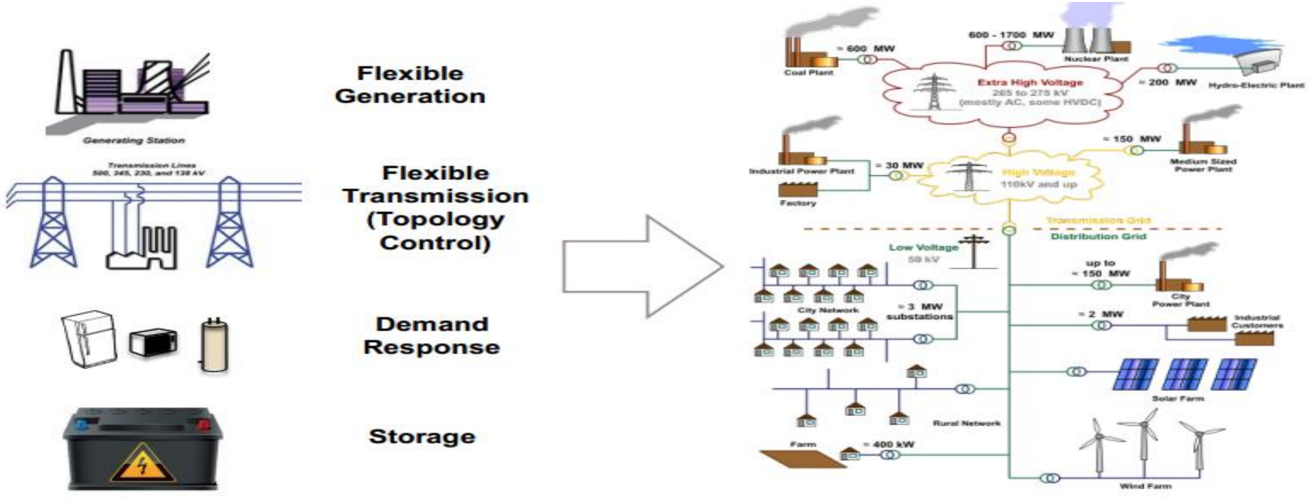


Figure 2-13. Possible solutions: way-out in diagram

2.8. Integrated renewable energy systems

The contribution of renewable resources to the energy portfolio globally has been steadily growing over the past few years [4]. IRES are systems that harness two or more forms of locally available renewable energy resources to supply a variety of energy demand in an efficient, cost- effective and practical way. Such systems can operate well in both off-grid/stand-alone mode and when connected to a centralized grid. RESs are highly site-specific, stochastic in, and unevenly distributed around the world with little or no costs. They depend on the climatic conditions, geographical factors and seasons of the site under consideration [31].

Due to the increasing level of uncertainties introduced by renewable energy sources (RESs), traditional deterministic decision making in the electric power industry is gradually shifting towards stochastic decision making which explicitly considers the uncertainty in the power output of RES generators.

The most widely used renewable resources as inputs to RES are biomass, hydro, solar, wind, and geothermal. The prime significance of RES is its focus to energize and electrify remote rural areas as promoted by hybrid systems, in order to achieve sustainable development and improve the basic living of communities [17] [57]. Several renewable integration studies have focused on optimization requirements of power system with high renewable penetration such as wind [75] [76] gas [36] natural gas [58] and photovoltaic (PV) [12]. In this PhD dissertation, IRES comprising biomass, large and micro-hydro plants, solar PV, solar thermal, waste to energy plant, wind farm, and geothermal with their problem formulation and constraint handling mechanisms are discussed.

Chapter 3. Security Constrained Economic Dispatch of Integrated Renewable Energy Systems: Approaches

3.1. Introduction

Optimization is the act of obtaining the best result under given circumstances with the ultimate goal of either minimizing the effort required or maximize the desired benefit. Mathematically, optimization deals with finding maxima and minima of a function possibly subject to constraints. It is mostly used to determine the best solution without actually testing all possible scenarios. A particular optimization problem is comprised of an objective function, design constraint function, design vector and design space. The choice of the optimization method depends on many factors, such as the type of objective function (nonlinear/linear, smooth/non-smooth, convex/non-convex, etc.) as well as the design constraints. SCED is a nonlinear, multi-objective optimization problem that can be solved using mathematical programming-based optimization techniques[39] [51].

When taking into account practical optimization problems with valve-point effects or prohibited operating zones, the resulting cost function is non-smooth or nonconvex. In this case, most of the mathematical optimization techniques are not suitable for solving the SCED problem [77]. Works that are more recent have focused on artificial intelligence (AI) methods, in parallel with the development of AI optimization theories. Many of AI techniques have proven their effectiveness in solving the Dynamic Economic Dispatch (DED) problems without any or few restrictions on the shape of the cost function curves as well as constraints [39] [77].

3.1.1. Objective function

The objective function also known as criterion or merit function is the criterion with respect to which the design is optimal when expressed as a function of design variables. It is the function that relates the objective required to be achieved and the design variables involved. This function can be single, multi-variable with a single objective, or multi-objective.

An objective function for optimization is formulated as:

$$\text{Find x, which minimizes } f(x)=\begin{Bmatrix} x_1 \\ x_2 \\ . \\ . \\ .x_n \end{Bmatrix} \tag{3-1}$$

Subject to

$g_i(x) \leq 0$, i=0, 1, 2, 3…m (3-2)

$L_i(x) = 0$, i=0, 2, 3…p (3-3)

This is a typical example of a constrained optimization problem with an objective function $f(x)$, equality constraint $L_i(x) = 0$, inequality constraint $g_i(x) \leq 0$, and n-dimensional vector of x called design vector. Certain parameters are usually fixed at the outset and these are called pre-assigned variables. All the other parameters are considered as variables in the design process and are called design or decision variables $x_i, i = 1, 2, \ldots n$.

These decision variables are grouped to form a design vector $x = \{x_1, x_2, x_3 \ldots x_n\}$. A practical example of an optimization problem is the economic dispatch problem in power systems operation. Its objective functions aim to minimize operating cost with variables of power output from each generating unit and constraints such as system load demand, power balance and generating capacity.

3.1.2. Design constraints

The restrictions and limits that must be satisfied to produce an acceptable design are collectively called design constraints. Upper and lower bounds depending on the physical limitations are called side constraints. Equality and inequality constraints in an optimization problem are because of restriction on the mathematical formulation of the variables [78]. There are also geometric and behavioral constraints.

3.1.3. Need of optimization in power system

A power system is required to be secure, economical, and reliable meaning that all operating conditions should be at the optimum point in power system operation. Optimization in power systems can be utilized for:

- Power flow analysis
- Load shedding
- Configuration of electrical distribution networks
- Unit commitment and economic dispatch

Example 3.1. In this example, the relationships between the computational problems in power systems and the basic concept of optimization are illustrated.

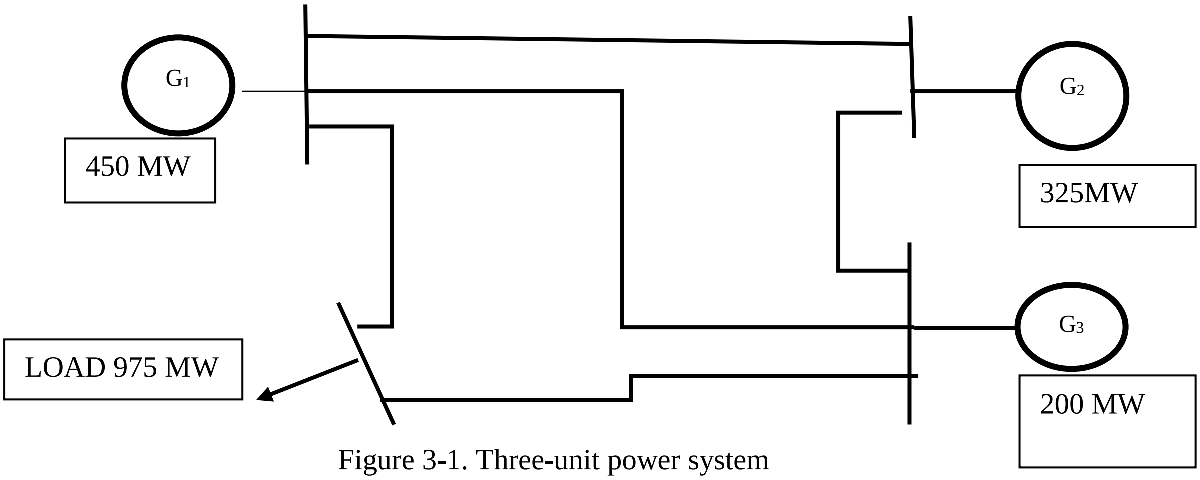


Figure 3-1. Three-unit power system

Objective function: $\min f(x)$

Where $f(x) = f_c(P_{G1}) + f_c(P_{G2}) + f_c(P_{G3})$

Subject to

$$P_{G1} + P_{G2} + P_{G3} \geq 975MW$$

$$P_{G1} \leq 450MW$$

$$P_{G2} \leq 325MW$$

$$P_{G3} \leq 200MW$$

$$f_C(x) = \alpha_1 \sum_{i=1} f_{Ci} + \alpha_2 \sum_{i=1} P_{loss}$$

Where $\alpha_1 + \alpha_2 = 1$

$$\frac{d^n f(x)}{d(x)} > 0 \text{, local maximum}$$

$$\frac{d^n f(x)}{d(x)} \leq 0 \text{, local minimum}$$

3.2. SCED objective function formulations

Traditionally, SCED problem is normally solved by discretization*** of the entire dispatch period into a number of minor intervals, over which the load demand is assumed to be constant and the system is known to be during a temporal steady state. In each time interval, a SED problem is solved under static constraints and then the ramp rate constraints are enforced between the consecutive intervals. In the SCED problem, the optimization is done with respect to the dispatchable generating units of a given power system [27].

3.2.1. Formulations with respect to conventional generation

In the conventional methods, the input-output characteristic of thermal generators is typically approximated by quadratic functions or piecewise quadratic functions, which are unfortunately far from the practical modern plants. The total operating cost of the power system with respect to conventional generation is represented by the following polynomial:

$$F_T = \sum_{i=1}^{N} F_i(P_{Gthi}) = \sum_{i=1}^{N} (a_i P_{Gthi}{}^2 + b_i P_{Gthi} + c_i) \tag{3-4}$$

3.2.2. Formulations with respect to RES penetration

Since the input–output characteristic equations of generators, units and system power losses are nonlinear functions, the real power SCED model is a nonlinear function. When this optimization problem is applied for intermittent, mixture of dispatchable and non-dispatchable RESs, it needs to address the effect of variabilities from both the generation and demand sides. Finding optimal allocation with minimum production cost and maximum security of the optimization problem is the part assigned for simulation [15].

Relations between the cost of generating power and the operating cost that rely on power flow output and forecasted values for the load demand are determined for each dispatch interval [79] [80]. Problem formulation thus starts from the optimization perspective of the SCED mathematical model. The general optimization problem form for SCED is:

$$\min f(x), x \in R^n \tag{3-5}$$

Subject to

$$h_k(x) = 0 \quad \forall k = 1, 2 \ldots m \tag{3-6}$$

*** **Discretization** is the process of transferring continuous functions, models, variables, and equations into discrete counterparts. This process is usually carried out as a first step toward making them suitable for numerical evaluation and implementation on digital computers.

$$g_l(x) \leq 0 \ \forall l = 1, 2 \ldots L \tag{3-7}$$

Where $h_k(x)$ represents equality constraints, $g_l(x)$ represents inequality constraints and x is the value that optimizes the objective function $f(x)$. In a practical power system, the SCED problem is non-linear and multi-objective due to operation and design constraints. Objective function should minimize non-detailed formulation of SCED problem due to the necessary assumptions that can lead to a limitation in the modelling of large-scale power systems. In light of this, multi-objective optimization is thus favored.

General form of multi-objective optimization is:

$$\min f(x) = (f_1(x), \ f_2(x), \ldots, \ f_{Nobj}(x)) \tag{3-8}$$

Subject to

$$h_k(x) = 0 \ \ \forall k = 1, 2 \ldots m \tag{3-9}$$

$$g_l(x) \leq 0 \ \ \forall l = 1, 2, \ldots K \tag{3-10}$$

$$x_i(\min) \leq x_i \leq x_i(\max) \tag{3-11}$$

Where $f_1(x), \ f_2(x), \ldots f_{Nobj}(x)$ is a set of different objective functions and $x_i(\min) \leq x_i \leq x_i(\max)$ denote security level constraints of the power system. Multi-objective optimization approach in SCED context refers to minimizing generation cost and maximizing the security level of the operating system while considering a variable generation [31]. The main objective of power systems operation is to supply consumers with electric power in a reliable way i.e. optimal loading is required to alleviate this mismatch. Each of the energy sources considered in this study, requires SCED problem formulation, and constraint handling mechanisms as discussed below.

***Hydropower economic dispatch formulation*:** At the design stage**,** the available power at the hydraulic turbine (P_{hg}) depends on the effective area ($a_{effective}$) at the tip of penstock hitting the turbine and velocity of falling water (v).

$$P_{hg} = \frac{1}{2} a_{effective} \rho v^3 \tag{3-12}$$

To formulate economic dispatch formulation, the first objective function,*$f_1(x)$*, in equation 3-8 represents objective function of hydro power generation plants [56].

$$\min\ f_1(x) = C_h \sum_{i=1}^{N_{hg}} P_{hgj}(t) \tag{3-13}$$

Where C_h denotes hydropower generation cost of 1 MW, P_{hgj} represents hydropower output at the i th unit, and N_{hg} are the number of committed hydropower plants. Hydropower generation mainly depends on the average head H_{ij} and water discharge outflow Q_{ij} . C_h constitutes operation and maintenance cost (~ 2-2.5 % of installed cost for large hydro and~ 1-4% of installed cost for small hydro), salary, wages and refurbishment cost (1-6% of installed cost). These coefficients depend on average investment cost, installed costs, and O&M costs. Knowledge of these costs enables us to determine Levelized Cost of Energy (LCOE), Locational Marginal Prices (LMP), and node injection prices.

$$P_{hgj}(t) = \sum_{t=1}^{24}\sum_{i=1}^{N_G} 0.00981\eta_i H_{ij} Q_{ij} \tag{3-14}$$

Wind power economic dispatch formulation: The average wind power (P_{wav}) is determined by:

$$P_{w_{Ave}} = \int_0^T P_w(v_w)\, dv_w \tag{3-15}$$

To develop a complete model of the SCED, it is imperative to characterize the stochastic nature of wind speed to analyze the problem with numerical results. Therefore, the Weibull probability density function is used to capture their stochastic nature. In compliance with the Weibull probability distribution function, the deviation of individual wind speed averages (σ_{v_w}) should be calculated to determine the average wind speed.

$$\sigma_{v_w} = \sqrt{\frac{1}{N_{v_w}} \sum_{i=1}^{N_{v_w}} \left(v_{wi} - v_{w_{a\,\mathrm{var}\,age}} \right)^2} \tag{3-16}$$

Accordingly, the average wind speed for first stage decision can thus be determined by

$$v_{w_{a\,\mathrm{v}\,ge}} = \frac{1}{N_{v_w}} \sum_{i=1}^{N_{v_w}} v_{wi} \tag{3-17}$$

The output power of a wind turbine depends on the wind speed at the site as well as the parameters of the power performance curve. For a particular site, rated power output of assumed wind speed is given by [76] 21]:

$$P_{wr} = \begin{cases} 0, \; for v_{wt} \leq v_i and v_{out} \geq 0 \\ P_{wr}(\frac{v_{wt} - v_i}{v_r - v_i}), \; for v_i \leq v_{wr} \leq v_{out} \\ P_{wr}, \; for v_r \leq v_{wt} \leq v_{out} \end{cases} \tag{3-18}$$

Here, v_i , v_{out} , v_r , v_{wt} , and P_{wr} represent cut-in wind speed, cut-out wind speed, rated wind speed ,forecasted wind speed and rated wind power output respectively. For the second objective function formulation $f_2(x)$, the cost of wind generation is given by:

$$\min \; f_2(x) = C_w \sum_{i=1}^{N_{WG}} P_{wgj}(t) + \sum_{t=1}^{24} \sum_{i=1}^{N_{WG}} (C_R + C_P) \tag{3-19}$$

Where C_w , P_{wgj} and N_{WG} represent wind power generation cost of 1 MW, wind power output at the j^{th} unit and number of committed wind generating units, respectively. C_R and C_P defined by $C_R = C_{Rw} + P_w(t) - (P_{wr}(t) - \alpha v_r)$, $C_P = C_{Pw} + ((P_w(t) - \alpha v_r) - P_{wr}(t))$ represent the reserve cost function and penalty cost function of wind power generation, respectively. Reserve cost function helps to determine the debit that can be produced from the probability distribution function of variable wind speed [28] [39].

Penalty costs are due to the mismatch between the actual and scheduled wind and PV power outputs, which depend on the stochastic nature of wind speed and solar irradiance. The probability distribution function for the power output of variable wind in the range of ($v_i \leq v \leq v_r$) can be determined by:

$$f_{pw} = \frac{K_{rvi}}{P_{wc}} \left[\frac{1 + \frac{h_{Pw}(v_t)}{P_{wr}}}{C} \right]^{K-1} xe^{\left[\frac{h_{Pw}(v_t)}{P_{wr}} \right]K} \tag{3-20}$$

Where K and C are Weibull probability distribution factors.

$$K = (\frac{\sigma}{v_m})^{-1.086} \tag{3-21}$$

$$C = \frac{V_m}{T(1 + \frac{1}{K})} \tag{3-22}$$

***Solar PV economic dispatch formulation*:** The solar power output that can be extracted from a given solar irradiance G is [41] [81]:

$$P_{sg} j(t) = P_{sg}(G) = P_{sr} j(\frac{G^2}{G_{std} + R_{ca}}) \tag{3-23}$$

In this equation G, G_{std}, P_{sg}, P_{sr} and R_{ca} denote solar irradiance, solar irradiance in a standard environment, solar output, rated solar output and certain irradiance point set at 150 W/m^2, respectively [57]. $P_{sg}\, j(t)$ represents the solar output power of the jth generating unit at a time t. And its corresponding objective function considered as the third objective function in equation 3-8 is represented by *f*$_3$*(x)*.

$$\min\ f_3(x) = C_s \sum_{i=1}^{N_{sg}} P_{sg}\, j(t) + \sum_{t=1}^{24} \sum_{i=1}^{N_{sg}} (C_R + C_P) \tag{3-24}$$

Where C_s solar power generation cost of 1 MW and for 0 <G< R ca the above equation becomes:

$$P_{sg}\, j(t) = \sum_{t=1}^{24} \sum_{i=1}^{N_{sg}} (C_R + C_P) \tag{3-25}$$

C$_R$ and C$_P$ defined by $C_R = C_{RS} + P_S\, j(t) - (P_{Sr}\, j(t) - \alpha V)$, $C_P = C_{PS} + ((P_S\, j(t) - \alpha V) - P_{Sr}\, j(t))$ represent the reserve cost function and penalty cost function of solar PV generation, respectively. Reserve cost function helps to determine the debit produced from the probability distribution function of variable solar radiation. The probability distribution function for the power output of variable solar irradiance can also be determined using the Weibull probability distribution function given in equation 3-20 [48] [42].

Renewable thermal power economic dispatch formulation*:* Renewable thermal plants in this context refer to plants adopted from conventional thermal plants that are fueled by renewable sources. Despite the difference in their constraints, renewable thermal plants have similar objective functions [18][42]. Economic dispatch objective function of thermal power generation cost (F_{th}) is a quadratic function of constant coefficient measure of losses (a_i), constant coefficient representing fuel cost (b_i) and constant coefficient representing operating and maintenance cost that includes salary and wages (c_i). Denoting solar thermal power generation cost, geothermal generation cost and biomass generation cost by F_{Sth}, F_{Gth} and F_{Bth} respectively; the total objective function for renewable thermal power generators with their corresponding power outputs P_{Sth}, P_{Gth} and P_{Bth} is given by:

$$\min\ f_4(x) = C_{th} \sum_{i=1}^{N_{th}} P_{th}\, j(t) \left[\alpha_1 \sum_{i=1}^{N_{Gth}} F_{Gth} P_{Gth} + \alpha_2 \sum_{i=1}^{N_{Sth}} F_{Sth} P_{Sth} + \alpha_3 \sum_{i=1}^{N_{Bth}} F_{Bth} P_{Bth} \right] \tag{3-26}$$

In the fourth objective function, $f_4(x)$, the cost of geothermal generation (F_{Gth}), cost of renewable thermal generation (F_{th}), solar thermal generation coat (F_{Sth}) and biomass generation cost (F_{Bth}) are related with their respective power output using:

$$F_{th} = a_i P_{th}{}^2 + b_i P_{th} + c_i \tag{3-27}$$

$$F_{Gth} = a_i P_{Gth}{}^2 + b_i P_{Gth} + c_i \tag{3-28}$$

$$F_{Sth} = a_i P_{Sth}{}^2 + b_i P_{Sth} + c_i \tag{3-29}$$

$$F_{Bth} = a_i P_{Bth}{}^2 + b_i P_{Bth} + c_i \tag{3-30}$$

Where P_{th}, P_{Gth}, P_{Sth} and P_{Sth} denote thermal power output, geothermal power output, solar power output and biomass power output, respectively. Weight factors of unit costs between 0 and 1 are represented by α.

***Economic dispatch formulation for Security index*:** This objective function that shows the severity of contingency during outages can be formulated using the following equation.

$$\max\ f_5(x) = f_{SL} = \sum_{i=1}^{N_L} \left(\frac{P_{Gactive}}{P_{Gactive}^{\max}} \right)^{2m} \tag{3-31}$$

Where N_L denotes the total number of transmission lines $P_{Gactive}$ and $P_{Gactive}^{\max}$ represent active power flow and maximum active power flow at the k^th^ line respectively. This proposed method can alleviate the number of recursive blackouts so as to restore the power balance after a generation failure; enough backup capacity has to be kept standing by, as a contingency reserve[†††].

As the computational solution methods for optimization problems keep changing and advancing, the formulations of their respective objective functions and constraint functions should also change and advance. SCED formulation for Newton Raphson solution method and for genetic algorithm are completely different. SCED formulations and mapping objective functions to be solved by different artificial intelligence techniques varies. In this dissertation, the objective functions and constraint functions are written in separate sections to cope up with the mapping requirements of genetic algorithm and Hopfield neural network.

[†††] Note that other online reserves, e.g. frequency regulation reserves, are also spinning, which may create confusion given the lack of uniformity on the definitions of generation reserves.

3.3. Constraint formulations

The following constraints[‡‡‡] have been considered in the ED problem: load demand balance, ramp rate limits, generation capacity, spinning reserve requirement, security constraints, emission constraints, prohibited operating zone constraints, etc. Comprehensively, these constraints are categorized into three kinds: equality constraints, inequality constraints, and dynamic constraints. Some of these constraints such as the load demand balance, and spinning reserve constraints can be modified when the SCED problem is solved in the deregulated market environment. In power systems, continuously respected operation constraints and limits ensure a reliable and secure operation of the system.

1. Demand and generation balance

Demand must be equal to the sum of the total generation and power lost transporting it. Power and demand balance mainly depends on total demand (P_D), total generation (P_G) and power transmission line loss (P_L). The total demand sums up all outputs from different resources such as hydro (P_{hg}), wind (P_{wg}), solar PV (P_{sg}), and renewable thermal (P_{th}).

$$P_D + P_L = \sum_{i=1}^{N_{hgg}} P_{hg} + \sum_{i=1}^{N_{wg}} P_{wg} + \sum_{i=1}^{N_{sg}} P_{sg} + \sum_{i=1}^{N_{th}} P_{th} \tag{3-32}$$

Demand and generation balance clarifies that the total generation of hydro generating units (P_{hg}),wind generating units(P_{wg}), solar units(P_{sg})and thermal units(P_{th}) should be equal to the sum of total demand (P_D) and power loss (P_L).

2. Generation limits:

Generation limits are used to limit the maximum and minimum generation capacity, prescribed value, of each generating unit. These limits prevent the flow on any line not to exceed its capacity. For stable and secure power system operation, the power output of each generating unit must be restricted by lower and upper bounds. Every generating unit is subject to generation limit constraints.

$$P_i^{\min} \le P_i \le P_i^{\max} \tag{3-33}$$

[‡‡‡] The resources/generating units considered have common constraints such as demand supply balance, transmission constraints, penetration rate constraints, transmission limits etc. To reduce the complexity of SCED, Bender's Decomposition and Classifier Function (CF) fundamentals recommend that objective functions and constraint functions of SCED problem to be written separately.

$$P_{h\min} \leq 0.00981\eta_i H_{ij} Q_{ij} \leq P_{h\max} \tag{3-34}$$

$$0 \leq P_w j(t) \leq P_{wr} \tag{3-35}$$

$$0 \leq P_s j(t) \leq P_{sr} \tag{3-36}$$

$$0 \leq P_h j(t) \leq P_{hr} \tag{3-37}$$

3. Prohibited operating zones

Modern generators have prohibited operating zones for determining feasible operating zones. Prohibited operating zone constraints are added to the SCED problem due to the design restrictions or vibrations in a shaft bearing. For optimization purposes, these constraints can be understood as upper and lower bounds. The prohibited operating zone constraints are formulated as inequality constraints as:

$$P_i^{\min} \leq P_i \leq P_i^{Lj} \forall j = 1, 2 \ldots N_{Poz} \tag{3-38}$$

$$P_i^{V_j - 1} \leq P_i \leq P_i^{lj} \tag{3-39}$$

$$P_i^{V_j - 1} \leq P_i \leq P_i^{\max} \tag{3-40}$$

4. Transmission constraints

For transmission constraints, Kron’s loss equation is considered as the sum of the net injections at all buses must be equal to the power losses in the branches of the network. The location of a particular plant from the load center affects the cost of transmission losses. As the power transmission losses depend on the flows in the branches and on the net injections, Kron’s loss equation better describes these power injection parameters.

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{m} P_{gi} B_{ij} P_{gj} = B_{oo} + \sum_{i=1}^{n} B_{io} P_{gi} + \sum_{i=1}^{n}\sum_{j=1}^{m} P_{gi} B_{ij} P_{gj} \tag{3-41}$$

Where

$$B_{ij} = \frac{\cos(\theta_i - \theta_j) R_{ij}}{\cos\phi_i \cos\phi_j V_i V_J} \tag{3-42}$$

$$B_{oo} = \sum_{i=1}^{n}\sum_{j=1}^{m} P_{Di} B_{ij} P_{Dj} \tag{3-43}$$

$$B_{ij} = -\sum_{j=1}^{m}\left(B_{ij} + B_{ji}\right) \tag{3-44}$$

5. Security limits

Security limits refer to the principle of secure power system operation i.e. apparent power flow through the transmission line (S_1) must be restricted by its upper limit ($S_1^{\max}$) for all security levels (N_L). Security level depends on the credibility of contingencies ($\phi_j P(t)$).

$$S_1 \le S_1^{\max} \forall l = 1, 2 \ldots N_L \tag{3-45}$$

$$\phi_j P(t) > 0 \forall j = 1, 2 \ldots N_C \tag{3-46}$$

6. Generator ramp rate limits

Increasing and decreasing the output of renewable generation is limited to the amount of dependable power due to the physical and mechanical restrictions of each generating unit. Generator ramp limits change the effective operating limit to extend the life span of generators.

$$\max(P_i^{\min}, P_i^{t-1} - DR_i) \le P_i(t) \le \min(P_i^{\max}, P_i^{t-1} + DR_i) \tag{3-47}$$

7. Spinning reserve limits

To have a primary frequency response to variable demand, a minimum spinning reserve value must be set aside.

$$\sum_{i=1}^{N_G} S_{Ri} \ge S_{Sr} \tag{3-48}$$

Where S_{Ri} is the fraction of the total spinning reserve of the power system (S_{Sr}) allocated to the generating unit i

8. Water discharge and reservoir limits:

For hydrothermal generating units, bounds by the restrictions of their storage reservoirs must be considered. Hydropower plants can discharge a limited quantity of water in a predefined dispatch period.

$$X_i^{\min} \le X_i \le X_i^{\max} \tag{3-49}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{3-50}$$

$$Q_i^{\min} \le Q_{ij} \le Q_j^{\max} \tag{3-51}$$

$$V_i^{\min} \le V_{ij} \le V_j^{\max} \tag{3-52}$$

$$V_{i,j+1} = V_{ij} - (Q_{ij} - q_i + S_{ij})\Delta t + \sum_{K \in K_j} \left(Q_{ij} + S_{kij} + I_j\right)\Delta t \tag{3-53}$$

9. Renewable energy penetration rate constraints

$$P_w j(t) + P_s j(t) + P_h j(t) + P_{th} j(t) \le \Psi P_D \tag{3-54}$$

Constraint (9) considers renewable thermal generators (biomass, solar thermal, geothermal), hydro, wind, and solar PV penetration ratios ψ . And their energy share adopted from the Ethiopian energy system according to editing and adopting features of NREL-IEEE 118 bus system zones is given in the figure below [17] [82].

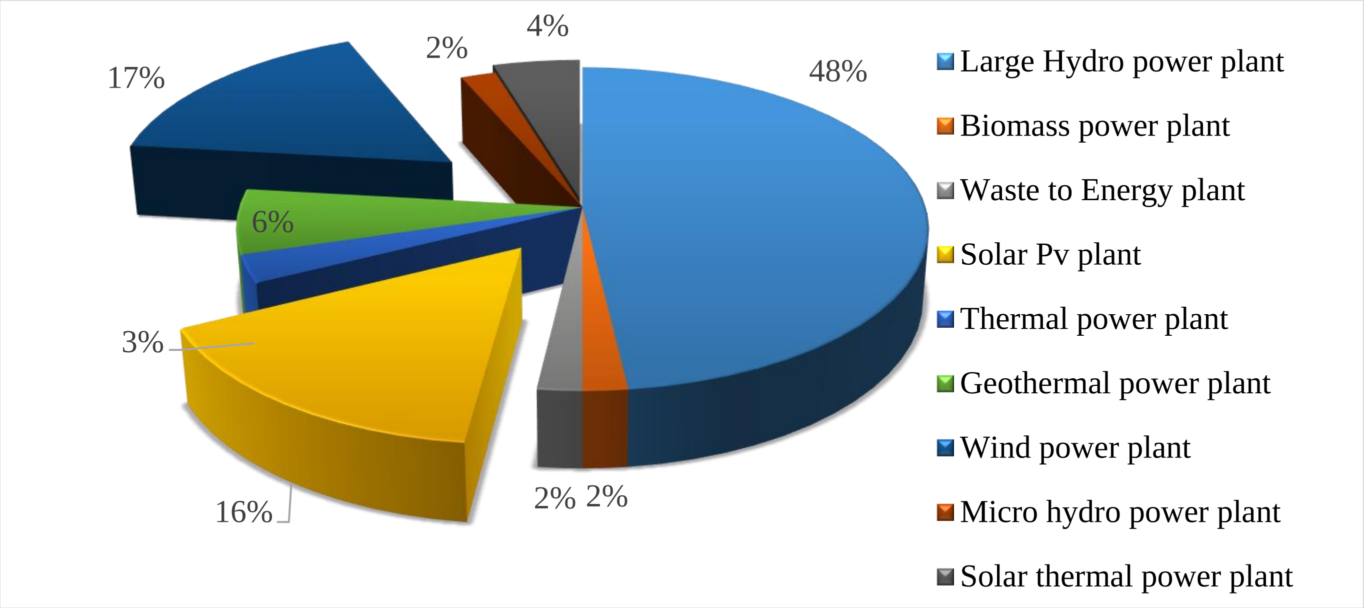


Figure 3-2. Energy share and penetration rate data of the considered Ethiopian renewable energy systems adopted according to NREL-118 bus system

The mathematical models presented in this chapter are used throughout this thesis to study and propose computationally robust and optimization-based techniques to better represent contingencies and constraints of SCED based auction models in competitive electricity markets.

Chapter 4. Optimal Security Constrained Economic Dispatch of Integrated Renewable Energy Systems: Methodologies

4.1. Introduction

Many approaches have been established to optimize the SCED of modern power systems with IRES. Some proposed approaches do not pay much attention to the impacts of generation uncertainty, which affects the system security, and renewable energy is only considered to serve the spot market in these methods. Solution methodologies of SCED widely vary from simple analytical to highly complex and theoretically sophisticated computations according to different approaches in the formulation. This section introduces the different solution methods studied so far by grouping them into three main categories.

a. *Analytical methods*

Usually, refer to the approximate solution obtained by variations of linear programming techniques or gradient and quadratic based methods. Substantial authors have studied considerable efficient algorithms in the applications of linear and nonlinear programming methods. Analytical methods include gradient methods, Newton's method, linear programming method, quadratic programming method and interior point method. Even though they have considerable drawbacks, analytical methods are effcient methods of determining the local optimum of unconstrained ideal optmization problems. However, practical SCED problems are multiobjective and highly non convex global optimization problems. To overcome these drawbacks, intensive studies have been conducted on computational intellegence methods.

b. *Computational intelligence methods*

For the last two decades, researchers have been looking for an optimization method with better global optimum searching performance and fast convergence. This quest paved a way to the understanding of Heuristic, or random search, optimization methods. These methods are increasingly being used for the solution of highly non-convex global optimization problems. They have the advantage of finding global optimum much faster than analytical methods but their inability to guarantee convergence causes skepticism for practical problems. Many of these techniques have been applied to SCED problems, including Ant Colony Optimization (ACO) [23], Artificial Neural Networks (ANN) [24] [25] [26] [27], Bacterial Foraging Algorithms (BFA) [28], Chaos Optimization Algorithms (COA) [29] [30], various Evolutionary Algorithms (EAs) [31], and Tabu Search (TS) [32]. Due to the drawbacks of deterministic criteria and unguaranteed convergence, hybrid methods, which model uncertainties, have been proposed to overcome these challenges.

c. *Hybrid methods*

Hybrid methods are the merger of two or more optimization algorithms to improve the overall performance of a single or multi-objective optimization problem. The main goal of developing hybrid methods is to achieve an improvement in terms of complexity and computational effort reduction on one hand and to increase the accuracy and robustness of the solution on the other hand. With the increasing interest of hybrid optimization methods, substantial articles have been published. Hybrid methods including bacterial foraging optimization, which is Nelder-Mead hybrid algorithm [28], improved harmonic search [33] and hybrid ACO-ABC HS algorithm [34] have clearly introduced an efficient and effective optimal solution to SCED problem. Irina [22] presented a hybrid, novel heuristic optimization algorithm called GAAPI, a combination of a special class of Ant Colony Optimization and Genetic Algorithm, to solve a large and complex optimization problem.

4.2. Multi-objective optimization

A multi-objective optimization problem is an optimization problem that involves multiple objective functions. In mathematical terms, a multi-objective optimization problem is often formulated as.

$$\min f(x) = (f_1(x), f_2(x), f_{Nobj}(x)) \tag{4-1}$$

Subject to

$$h_k(x) = 0 \ \forall k = 1, 2 \ldots m \tag{4-2}$$

$$g_l(x) \le 0 \quad \forall l = 1, 2, \ldots K \tag{4-3}$$

$$x_i(\min) \le x_i \le x_i(\max) \tag{4-4}$$

Multi-objective optimization is also an area of multiple criteria decision making that is concerned with mathematical optimization problems comprising multiple objective functions to be optimized simultaneously. Multi-objective optimization has been applied in many fields of science, including engineering, economics and logistics where optimal decisions have to be taken within the presence of trade-offs between two or more conflicting objectives.

4.3. Genetic algorithms

Genetic Algorithms (GAs) are adaptive search techniques based on the Darwinian notion of natural selection that starts with a population of randomly generated solution with little knowledge of correction. Importing parallel algorithm into GA can be more manageable in structural optimization. In most optimization problems, there are constraint conditions, but standard GA best fits for maximum search without constraints. Therefore, handling the constraints and objective functions, and subsequently establish a tractable fitness mapping function becomes the most important matter of this algorithm [52][83].

The genetic algorithm operates by randomly selecting pairs of individual chromosomes to reproduce for the next generation. The probability of a chromosome being selected is proportional to its fitness function value relative to the other chromosomes within the same generation. To reproduce, a crossover procedure is defined. In the classical GA, two chromosome strings reproduce by selecting a random bit for the crossing site, the strings are sliced at the site, and the two tailpieces are swapped and rejoined with the headpieces to produce two progenies [52].

a. Initialization

Initialize with random population. Each random chromosome of the population, representing a possible solution for the problem, is then evaluated using an objective function. The selection of this objective function is important because it practically comprises all the knowledge of the problem to be solved. The user is supposed to choose the proper combination of desirable attributes that could be the best fit for this purposes.

For SCED, initialize the number of generating units, N, and population size, $N_{P,}$ and specify credible contingencies. Population size and dimension randomly generate an initial vector P^t_{ij}. P^t_{ij} is the real power value of jth unit of the ith population randomly generated within the operating limits using [17];

$$P_{ij}^{t} = P_{i}^{\min} + rand(0,1)(P_{i}^{\max} - P_{i}^{\min}) \quad (4\text{-}4)$$

b. Selection Strategy

The fitness function is very imperative to the genetic algorithm search. Inappropriate fitness function may lead to premature convergence or generates the locally optimal solution but not the globally optimal solution. If minimization is chosen, the fitness function is directly equal to the objective function. However, if the maximization option is selected it is necessary to map the objective function *f(x)* into fitness function *fit(x)*.

$$fit(x) = {}^{1}\!/\!{}_{\alpha_{genetic} + f(x)}, \alpha_{genetic} = 0.00001 \quad (4\text{-}5)$$

$\alpha_{genetic}$ is introduced to avoid overflow problems if the objective function goes to a very small value. For the problem of collision detection, the target function is the problem of minimum value, hence the fitness function is formulated as.

$$Fit(fit(x)) = \begin{Bmatrix} 2 - f(x) \rightarrow iff\, ,\, f(x) < 2 \\ 0 \rightarrow else \end{Bmatrix} \tag{4-6}$$

2 is the estimation of the maximum value of f(x). Each entity in the population has a selective probability, which is determined by the fitness and the distribution of the fitness [19]. EPGA uses proportional fitness assignment, in order that the entity with higher fitness has a higher survival probability. Evaluate the fitness value of each vector P^t_{ij} according to the fitness function given below:

$$F_A = -(f_1(x) + f_2(x) + f_3(x) + f_4(x) + f_{Penality} + f_{\mathrm{Re}\,serve} + f_{loss}) \tag{4-7}$$

The specific steps are as follows.

1. Calculate the fitness of each entity as the fitness function & suppose that the fitness of entity i is singed as fi
2. Calculate the selective probability and cumulative odds of every entity.
3. Divide the extent of [0, 1] according to the cumulative odds.
4. Generate a random number between 0 and 1. If the number meets the condition of equation 4-8, choose entity i to copy.

$$\sum_{j=1}^{i-1} f_j \Big/ \sum_{j=1}^{pop-size} f_j < \zeta < \sum_{j=1}^{i} f_j \Big/ \sum_{j=1}^{pop-size} f_j \tag{4-8}$$

5. Repeat step (4) until the number of entity meets the demand.

c. Crossover and Mutation

The crossover strategy crosses the number bit-by-bit according to the crossover probability named p_c. First, choose two entities in the population randomly to combine into a pair. Second, choose a position randomly. And then generate a random number in [0, 1]. If the random number is greater than p_c, cross the number at the selected position, otherwise, keep the original state.

Mutation is a local random search method. Combined with the crossover, it can increase the efficiency of the genetic algorithm. It also makes genetic algorithm have the capability of searching in a random manner. Simultaneously, mutation can make the genetic algorithm maintain capable diversity to prevent premature convergence.

First, select an entity and then a position to mutate. Secondly, generate a random number in [0. 1]. If the random number is outside limits, put the operation of the mutation at the selected position, otherwise keep the original state [19].

$$p_c = \begin{Bmatrix} p_{c1} - {}^{(p_{c1} - p_{c2})(f' - f_{avg})}\!\big/\!_{(f_{\max} - f_{avg})} \rightarrow f \geq f_{avg} \\ p_c \rightarrow f < f_{avg} \end{Bmatrix} \tag{4-9}$$

$$p_c = \begin{Bmatrix} p_{c1} - {}^{(p_{c1} - p_{c2})(f' - f_{avg})}\!\big/\!_{(f_{\max} - f_{avg})} \rightarrow f \geq f_{avg} \\ p_c \rightarrow f < f_{avg} \end{Bmatrix} \tag{4-10}$$

Perform mutation operation on the target vectors to obtain new parameter vectors called mutant vectors using:

$$Z_{ij} = P_{ij}^{t} + F(P_{Rij}^{t} - P_{Rji}^{t}) \tag{4-11}$$

d. Reproduction

Reproduction involves creation of the latest offsprings from the mating of two selected parents or mating pairs. The crossover operator is mainly responsible for the global search property of the GA. An arithmetic crossover operator that defines a linear combination of two chromosomes was used. Two chromosomes selected randomly for crossover C_i^{gen} and C_j^{gen} can produce two offsprings C_i^{gen+1} and C_j^{gen+1} , which is a linear combination of their parents i and j.

$$C_i^{gen+1} = aC_i^{gen} + (1-a)C_j^{gen} \tag{4-12}$$

$$C_j^{gen+1} = (1-a)C_i^{gen} + aC_j^{gen} \tag{4-13}$$

Then, perform crossover operation to create trial vectors from mutant and target vectors. If the generated random value is less than or equal to the assumed value of the crossover constant, then the mutant vector is chosen, else the parent vector is chosen as given below. The assumed crossover constant (C_R) should be within the range of (0,1) [84].

$$U_{ij}^{t+1} = \begin{Bmatrix} Z_{ij}, if(R_{ij}) < C_R \\ Z_{ij}, if(R_{ij}) \geq C_R \end{Bmatrix} \tag{4-14}$$

e. Replacement

After the process of selection, crossover, and mutation, the new population replaces the current population. The fittest individuals of each generation are more likely to survive in the next generation. This means only the new individuals whose fitness values are better than those of the current will be replaced.

Non-dominated solutions known as pareto optimal solutions are defined as feasible solutions that no other feasible solution is strictly better than it with respect to all objectives. The plot of the objective functions whose non-dominated vectors are in the pareto optimal set is called pareto front. Any point on the pareto front is an optimal solution and it guarantees a secure power system with respect to the considered credible contingencies.

Finally, decide members to constitute the population of the next generation (t +1). The new vector $U_{ij}^{(t+1)}$ is selected based on the comparison of fitness of both target vector, P_i and trial vector, U_i. Compute generation after generation to meet the stopping criteria t_{max} [85].

The step by step algorithm for EPGA based SCED is:

a) Initialize with random population, initialize the number of generating units, N, and population size, N_P, and specify credible contingencies using equation 4-4.
b) Evaluate all initial and input conditions for GA operators such as equation 4-5 and 4-6.
c) Compute the fitness of each entity as the fitness function & suppose that the fitness of entity i is singed as fi in parallel
d) Calculate the selective probability and cumulative odds of every entity.
e) Divide the extent of [0, 1] according to the cumulative odds.
f) Generate a random number between 0 and 1. If the number meets the condition of fi, choose entity i to copy.
g) Select an entity and then a position to mutate
h) Perform crossover operation to create trial vectors from mutant and target vectors
i) Repeat steps f, g and h until the number of entity meets the demand

f. Efficient parallel genetic algorithm flowchart

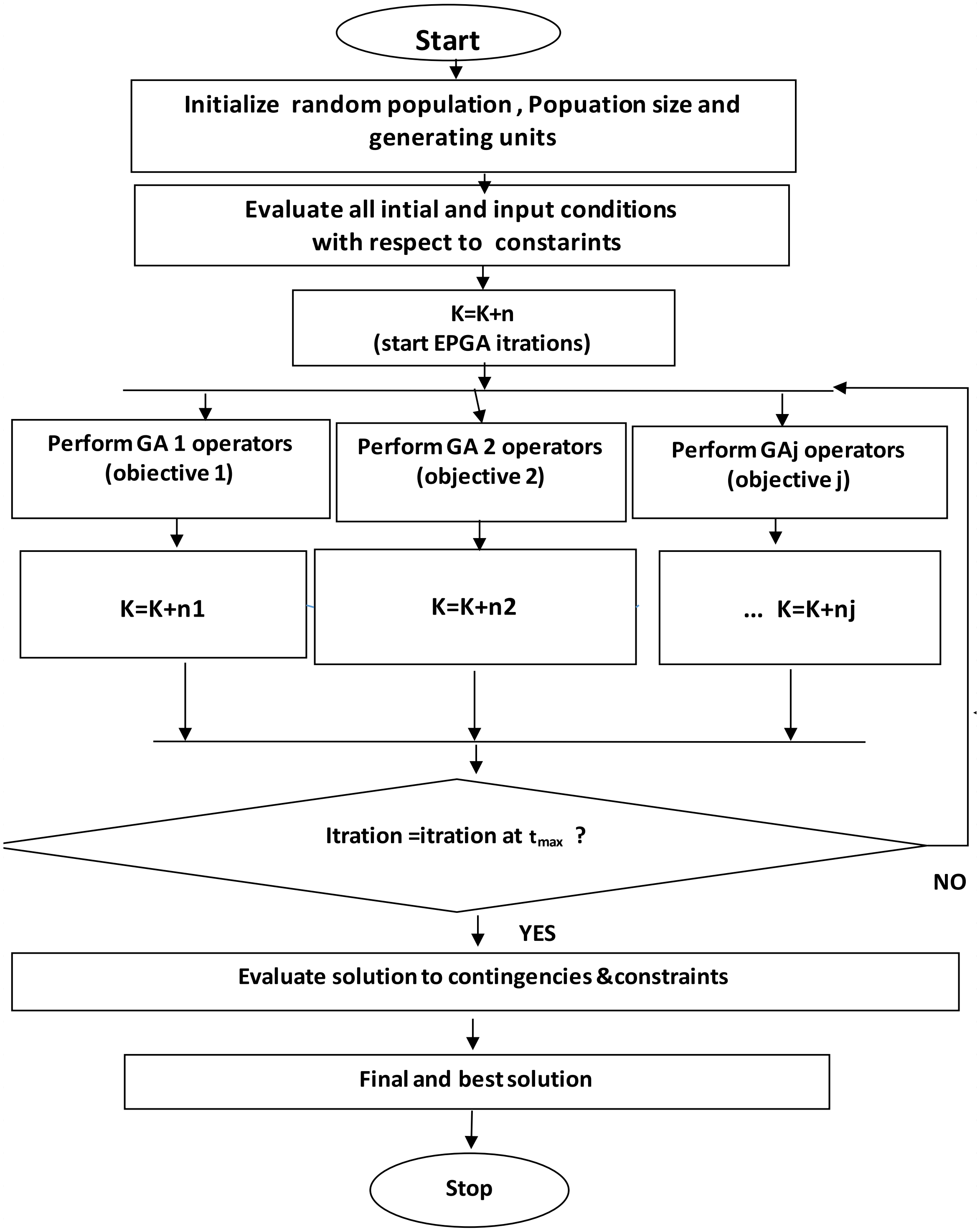


Figure 4-1. Flow chart for EPGA

4.4. Hopfield neural networks

Hopfield network is a recurrent artificial neural network in which all connections are symmetric. As it does not process sequences of patterns, it requires stationary inputs and is thus not a general recurrent artificial neural network. It is guaranteed that it will converge. If the connections are well trained, the Hopfield network can perform as robust content-addressable memory, resistant to connection alteration type optimization problems. The units in Hopfield networks are taken from two different values for their states. The value is decided by whether or not the units' input exceeds the predefined threshold. Every pair of units *i* and *j* in a Hopfield networks has a connection that is described by connectivity weight. In this case, the Hopfield network is described as a complete undirected graph [86] [87].

a) Initialization and running

Assigning values of the units to the desired start pattern initializes the Hopfield Networks. Iterative updates are then performed until the network converges to an attractor pattern. Convergence is generally guaranteed, as Hopfield network demonstrates that the attractors of this nonlinear dynamical system are stable, not periodic or chaotic. Therefore, in the context of the Hopfield Networks, an attractor pattern is a pattern that cannot change any value within it under updating [86].

$$V_i^0 = P_{Gi}^{\min} + rand(P_{Gi}^{\max} - P_{Gi}^{\min}) \qquad (4\text{-}15)$$

And, initial values of inputs for these neurons are calculated by using the inverse sigmoid functions

$$u_i^0 = \frac{1}{2\sigma}\ln\left(\frac{V_i^0 - P_{Gi}^{\min}}{P_{Gi}^{\max} - V_i^0}\right) \qquad (4\text{-}16)$$

b) Training

Training a Hopfield net involves reducing the energy states that the network should remember. This allows the network to serve as a content addressable memory system meaning the network will converge to a remembered state if it is given only part of the state. The network can be used as a recovery state from a distorted input to the trained state. This is known as associative memory as it recovers memories on the basis of similarity and place of their storage. Thus, the network should be properly trained when the energy of states that the network must remember are local minima [12]. Note that, contrary to perceptron training, the pre-specified thresholds of the neurons are never updated. There are no special input or output neurons in Hopfield network. All neurons have both input and output ports, and each neuron is connected to all other neurons in both directions with equal weights. Input can be applied to all neurons at the same time. The output of each neuron is then connected to all other neurons.

This procedure continues until a stable state representing the network's output is reached. HNN is the most widely used model for solving multi-objective and combinatorial optimization problems [8]. Two popular types of models, namely the discrete model and the continuous model are being applied recently. As the continuous model is favored for this study, figure 4-3 depicts its searching mechanism.

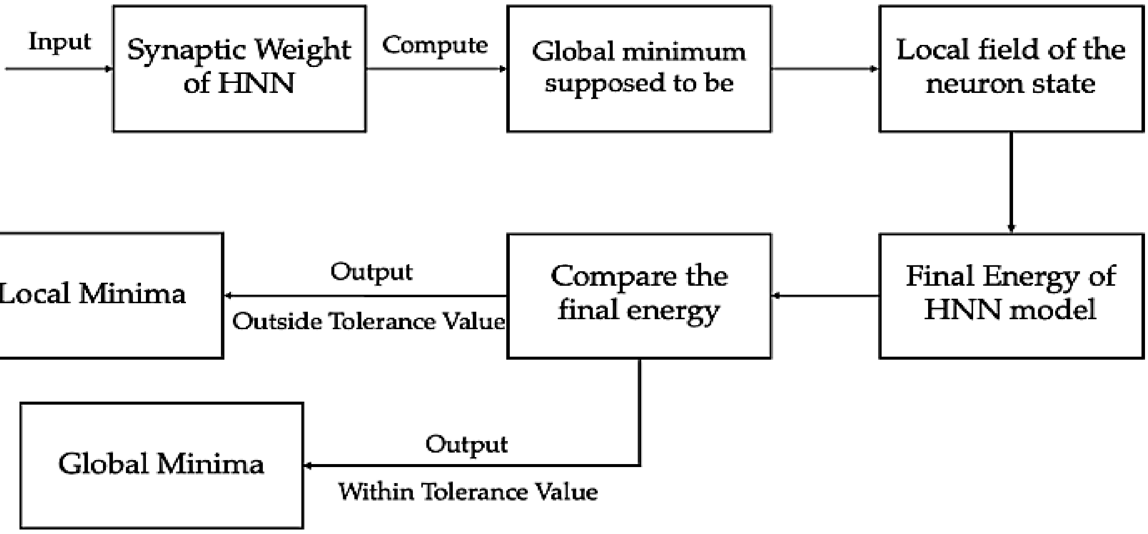


Figure 4-2. Searching mechanisms of continuous HNN model

The inputs to the neuron come from two sources, one from the external inputs Ii and the other from the other neurons Vj.

$$U_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} T_{ij} V_j + I_i \tag{4-17}$$

Where: U i is the total input to neuron i, Tij is the interconnection conductance from the output of neuron j to the input of neuron i, Ii denotes external input to neuron i, and Vj stands for the output of neuron j. The continuous or deterministic model of the Hopfield Neural Network is based on continuous variables.

c) Mapping Economic Dispatch to Hopfield Neural Network

Hopfield neural networks [12] have been employed to solve the SCED problem for generating units possessing continuous or piecewise quadratic fuel cost function [9] and [13], and even for units having prohibited zones constraint [14] and [15]. The objective function for the economic dispatch problem has two parts i) the operation and generation cost minimization part ii) the generation and computation error minimization part. To solve the economic dispatch problem, the energy function is defined by combining the objective function with constraints.

$$E = A(P_D + P_L - \sum_{i=1}^{N} P_G)^2 + B\sum(a_i + b_i P_{Gthi} + c_i P_{Gthi}{}^2) + \left(\frac{C}{2}\right) P_L{}^2 \tag{4-18}$$

The synaptic strength and external input are obtained by mapping the energy function. By changing the generation output of unit i from P_{Gio} to P_{Gi} and the transmission loss change from P_{Lo} to P_L. This can be represented by:

$$P_L = P_{Lo} + dP_L \cong P_{Lo} + \sum_{i=1}^{N} I_{Lio}(P_{Gi} - P_{Gio}) \tag{4-19}$$

Economic dispatch using Hopfield neural network requires a continuous neural model. Continuous Hopfield neural network has been used for economic dispatch of traditional generation with quadratic objective functions. In order to solve SCED the energy function of HNN must be defined by combining the objective function and the corresponding constraint function, by means of weight coefficients, which determine the weightage of each factor.

The energy function of HNN is given by:

$$E = -\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} T_{Ij}V_iV_j - \sum_{i=1}^{N} I_iV_i \tag{4-20}$$

The time derivative of this energy function is proven to be negative so the network always moves in such a direction that the function generally converges to a minimum. To solve SCED using HNN, the penalty function method is used to represent the number of online generators (N_G)

$$E = \frac{A}{2}\left(\sum_{i=1}^{N}(a_iP_{Gthi}{}^2 + b_iP_{Gthi} + c)\right) + \frac{B}{2}\left(P_L + P_D - \sum_{i=1}^{N} P_{Gthi}\right)^2 \tag{4-21}$$

This energy function consists of objective function also known as cost functions and design constraints function.

$$P_L = P_{Lo} + dP_L \cong P_{Lo} + \sum_{i=1}^{N} I_{Lio}(P_{Gi} - P_{Gio}) \tag{4-22}$$

$$\frac{\partial P_L}{\partial P_{Gi} P_{Gio}} = 2\sum_{i=1}^{N} B_{ij}P_{Gjo}(P_{Gi} - P_{Gio}) \tag{4-23}$$

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{Gio}B_{ij}P_{Gjo} + 2\sum_{i=1}^{N}\sum_{j=1}^{N} B_{ij}P_{Gjo}(P_{Gi} - P_{Gio}) \tag{4-24}$$

In order to map this equation into HNN, the computation should start by replacing V_i and V_j with P_{Gi} and P_{Gj} , so that the following set of equations are obtained.

$$T_{ii} = -Aa_i - B, T_{ij} = -B \tag{4-25}$$

$$I_i = B(P_D - P_L) - \frac{\lambda}{2} b_i \text{ or} \tag{4-26}$$

$$I_i = A(P_D + P_L) - \frac{Bb_i}{2} \tag{4-27}$$

Being A and B weighting factors, A varies from 0.1 to 3, B is set to 1, and λ is set to 0.000055. A and B should be greater than or equal to zero. The relation that updates these values is called adaptive calculation of weighting factors.

$$A = \frac{I_M + 0.5Bb_m}{P_G} \tag{4-28}$$

$$B = -\frac{I_M - AP_D}{0.5b_m} \tag{4-29}$$

Where,

$$I_M = \left(\frac{1}{N_G}\right) \sum I_{ED_i} \tag{4-30}$$

$$b_m = \left(\frac{1}{N_G}\right) \sum b_i \tag{4-31}$$

$$P_G = \sum P_{Gi}\ . \tag{4-32}$$

N_G is the number of committed generating units. In the selection procedure of weighting factors, A is associated with power mismatch (P_m), as it should be assigned the highest priority over the other terms.

$$A(P_m)^2 \geq B(\Delta f_T) \tag{4-33}$$

$$A \geq B(\Delta f_T) / (P_m)^2 \tag{4-34}$$

This means A can be determined from any value of B. To determine the value of weighting factor C.

$$C = 2AP_m \tag{4-35}$$

The step by step algorithm for HNN based SCED is:

a) Calculate initial values of input neurons using inverse sigmoid functions
b) Initialize network weights and map SCED to HNN's Energy function
c) Train the HNN to reduce the energy states that the network should remember
d) Create and compute HNN using "newhop" and Check synaptic weights, synaptic energy function mode and local field of the neurons of the created HNN
e) Is ΔE<1, and are constraints satisfied,
f) If no, the solution is outside the specified tolerance and then go back to d by training and updating the network with activation function and the attractor pattern.
g) If yes the solution is within the specified tolerance and stop to print the final solution

d) HNN flowchart

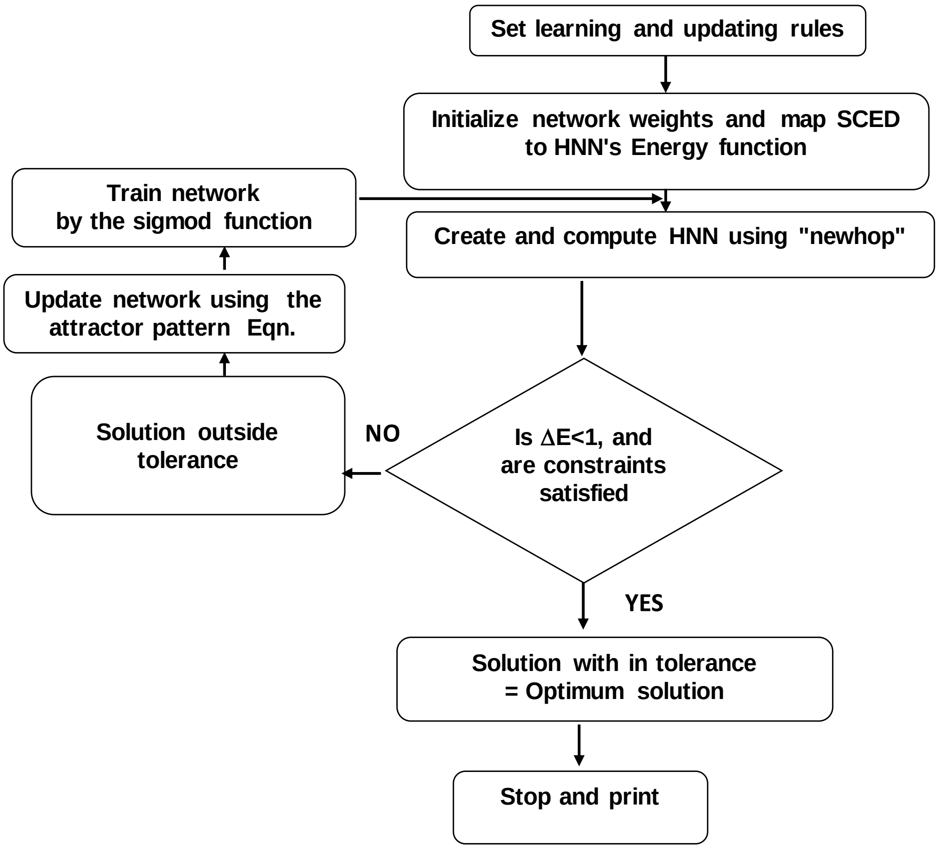


Figure 4-3. Flow chart for HNN

4.5. Hybrid Genetic algorithm-Hopfield neural network

Although the AI methods seem to be effective in solving the SCED problem, the obtained solutions are just near global optimum with long computation time. Hybrid methods merge two or more optimization techniques in order to combine their strengths and overcome one another’s weaknesses in solving the optimization problems. These hybrid methods are found to be effective in finding global optimal solution for the SCED with smooth/non-smooth or convex/nonconvex cost function. The proposed hybrid scheme is developed in such a way that a genetic algorithm acts as a base level search and a local search method is next employed to do the fine-tuning.

The main goal of developing hybrid methods is to achieve an improvement in terms of complexity and computational effort reduction on one hand, and increasing the accuracy and robustness of the solution on the other had. With the increasing interest in hybrid optimization methods, substantial articles have been published. Hybrid methods including bacterial foraging optimization that is Nelder-Mead hybrid algorithm [42], improved harmonic search, and hybrid ACO-ABC HS algorithm [43] have introduced an efficient and effective optimal solution to SCED problem [14].

Stephen Frank et al [44] have chronicled a bibliographic survey of papers with a perspective of non-deterministic hybrid methods for solving optimal power flow problems. Irina [37] presented a hybrid and novel heuristic optimization algorithm called GAAPI, a hybridization between a special class of Ant Colony Optimization and Genetic Algorithm, to solve a large and complex optimization problem. This dissertation proposes optimal SCED of RES using a robust and computationally intelligent GA-HNN approach adopted from [14] and [41], hybridization of Hopfield neural network, and improved genetic algorithms, which takes into account the intermittency of renewable energy sources and handles probable contingencies.

The general working algorithm for GA-HNN is:

1. Write separate objective functions and constraint functions.
2. Enter system data and analysis inputs using Weibull PDF equations and HNN predictive control.
3. Select A, B, λ and calculate their values
4. Determine the attractor pattern of the final state
5. Map the SCED objective functions to the HNN using penalty function weights as mathematically represented
6. Run adaptive calculations of weighting factors
7. Initiate genetic algorithms by selecting parameters such as population size and number of generation,

8. Compute parallel and consecutive genetic algorithm & check if the global best solution satisfies constraints and contingencies.
9. Display final and best solutions

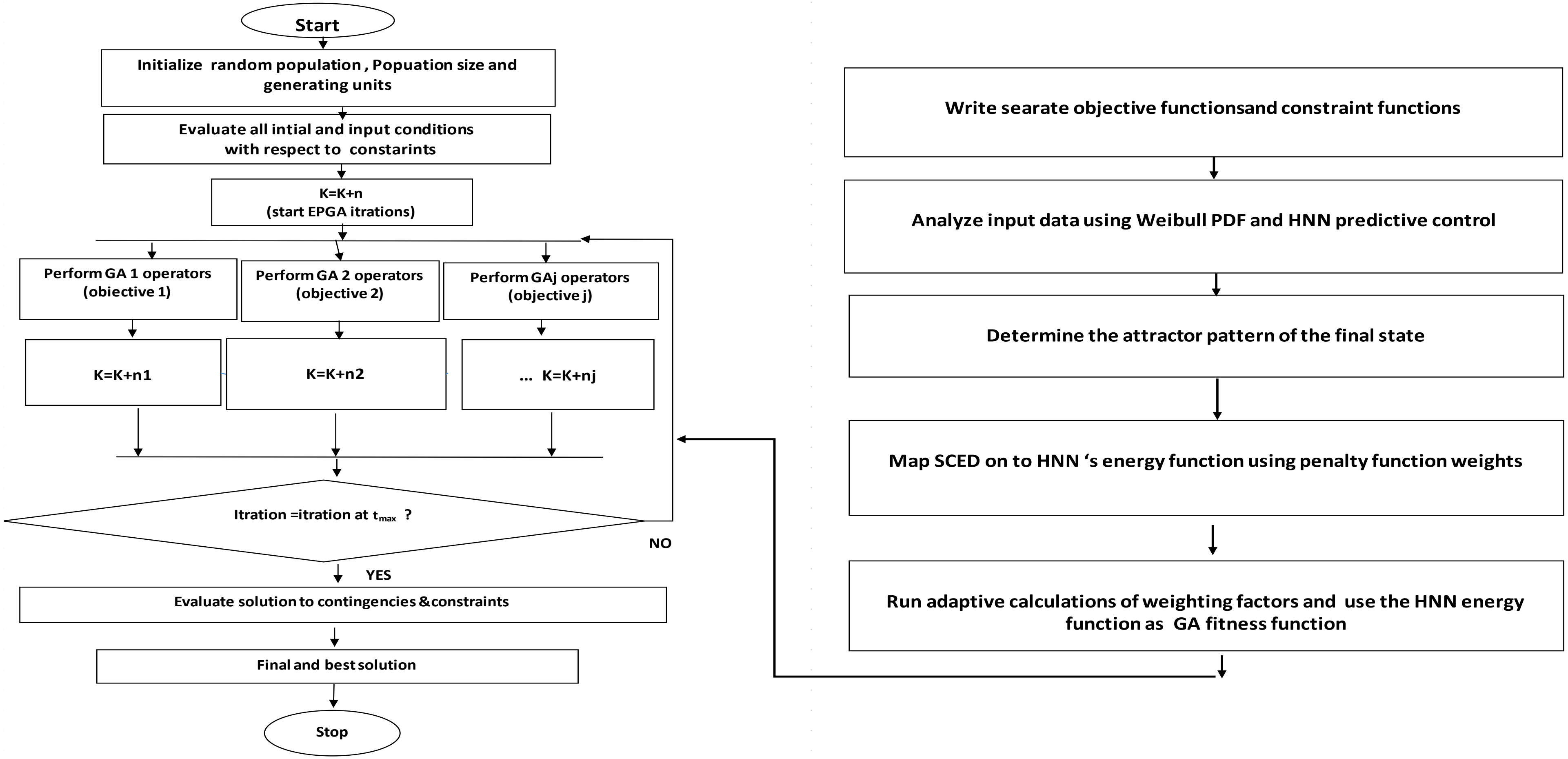


Figure 4-4. GA-HNN flow chart

Chapter 5. Case studies and test systems

5.1. Introduction

Detailed and reliable public databases of test power systems are highly valuable for researchers to conduct studies on new technologies and to test new algorithms. Several researchers use these databases for a number of crucial areas of power systems operation and planning, including: unit commitment, economic dispatch, congestion management, optimized allocation of distributed generation, fault detection, among many others. While test systems have limitations because of assumptions and simplifications, the models can inform electricity planning and market operation stakeholders, also policymakers, on the sensitivity of the system to critical variables. Test systems have been widely used in the research community because they provide standard public data, valuable for testing new algorithms, technologies, and control schemes.

5.2. Modified New England 39 bus system

This IEEE 39 bus system is well known as a 10-machine New-England Power grid. It has been considered in order to examine the effectiveness of the proposed SCED mathematical models and their respective solution methods. According to the book titled 'Energy Function Analysis for Power System Stability'[1], the network has 39 buses, 46 lines and 10 conventional generation units, and it is modified to include 4 wind generators connected to buses 5, 6, 14 and 17 as shown in Figure 5-1.

The renewable energy generators and their corresponding loads connected to different buses are considered to be uncertain. In total, there are 46 uncertain parameters in the network. The goal is to model active power and voltage amplitude of all controllable generators and the distribution vector α such that the generation cost is minimized while all the constraint of the network i.e. line flow, bus voltage and generators output constraint are respected with high probability [36] 85].

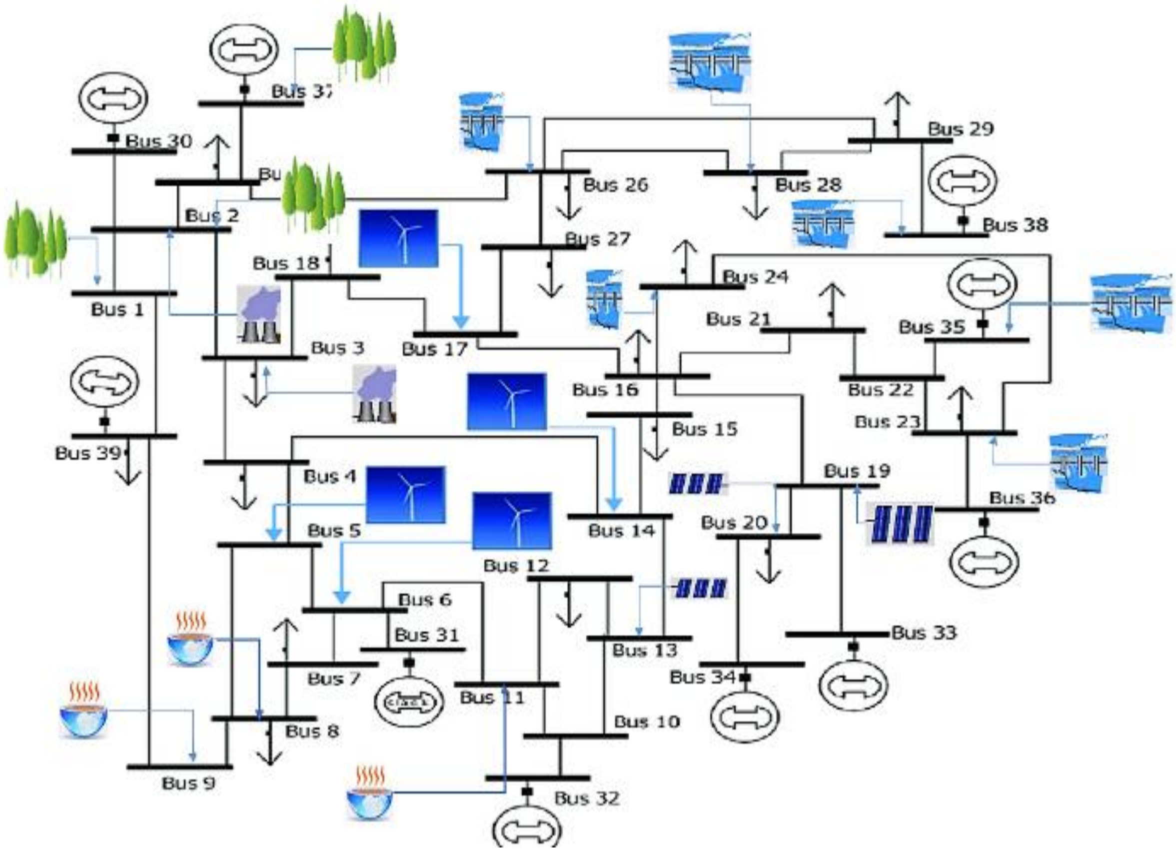


Figure 5-1. Modified New England 39 bus system

5.3. NREL-IEEE 118 bus system

While the existing IEEE test systems have been utilized to study a broad range of research topics, including economic dispatch models, congestion management and fault location, they often require extensive modifications to do so, and thus are no longer the standard system, and often lose most of their value for making direct comparisons between algorithms. The NREL-118 database presented allows for a broader range of use cases due to its higher data resolution, more detailed system characteristics (including differentiation of three separate regions and heat input functions for 10 power technologies), and time-series data for a full year that includes seasonal variations.

It also incorporates many of the challenges of integrating variable and uncertain renewable energy resources, expanding its utility to a new generation of power system problems. Modified database, named NREL-118 test system, using the transmission representation (buses and lines) of the IEEE 118-bus test system. A user can choose to edit the system components for his/her research purpose [82].

TABLE 5-1. LOCATION OF NREL-118 SYSTEM DATABASE

Type of data and type of energy conversion technology	**Link**
Solar, wind, hydro and load data	http://www.nrel.gov/esif/assets/docs/input-files.zip
System as .csv files and FAQ	http://www.nrel.gov/esif/assets/docs/additio nal-files-mti-118.zip
Plexos Model as plexos file	http://www.nrel.gov/esif/assets/docs/mti-118-mt-da-rt-reserves-all-generators.xml
Plexos model as .xls file	http://www.nrel.gov/esif/assets/docs/plexos-export.xls

The complete NREL-118 test system database can be considered in the community as a standard medium-size IEEE bus-test system, and certain variables, such as generator heat input and ramping functions, emission rates, fuel costs, and transmission line capacities, can be incorporated in other test systems. The new NREL-118 test system database can be used across different research topics allowing for consistency between results from different studies. In summary, the NREL-118 system includes the following information, which is currently not included in other public IEEE bus test systems:

- Detailed generation constraints (such as upward/downward ramping, minimum generation level, minimum up/downtimes, heat rate and fuel use at different load levels, start and shutdown costs).
- Time-synchronous yearlong actual and day-ahead forecast time series for wind and solar power as well as regional electricity load.
- Results from a unit commitment and economic dispatch model that simulates the operation of the test power system for one year with hourly resolution, including day-ahead unit commitments and real time commitment and dispatch decisions.

The NREL-118 system consists of three regions, each of which has a different load profile, and the resolution of the data is hourly for one full year [82].

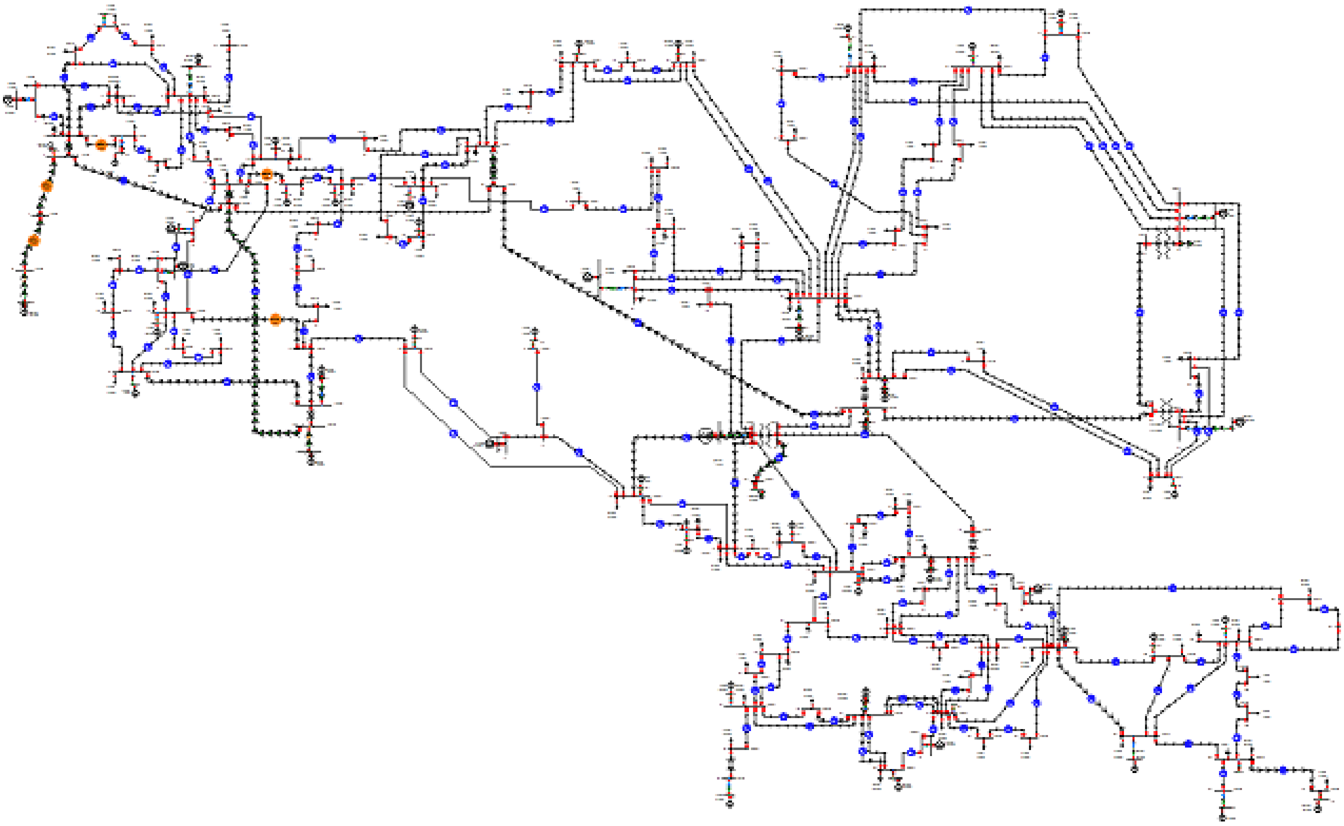
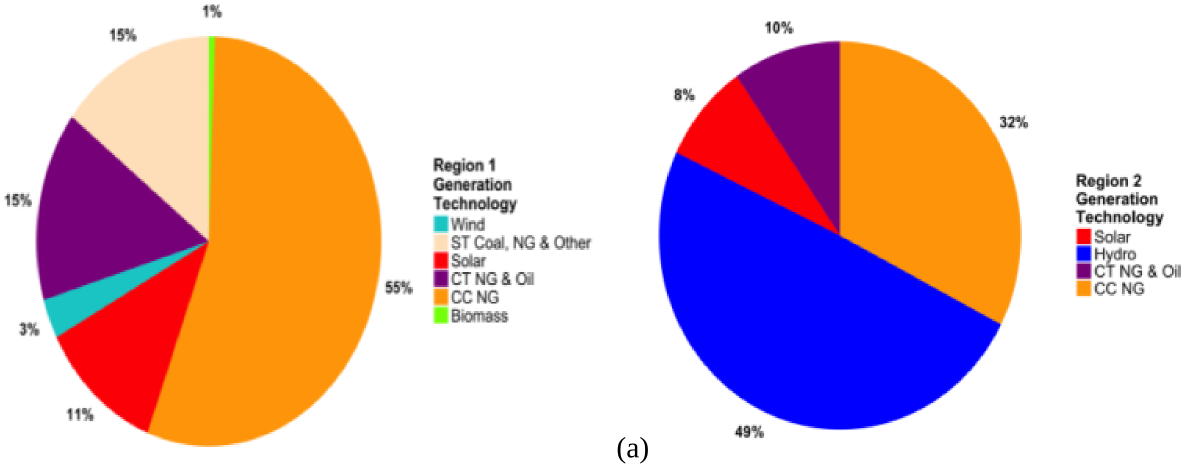


Figure 5-2. Modified IEEE 118 bus system(NREL -118 bus system)



(a)

(b)

Figure 5-3. Share of power generation (MW) in (a). Region 1 with a total electricity generation capacity of 10.5 GW (b). Region 2 with a total electricity generation capacity of 5.4 GW and [82].

5.4. Ethiopian power system

Access to reliable, secure, and affordable energy supply is a prominent prerequisite of the economic growth of a developing country like Ethiopia. Ethiopia is facing intimidating energy challenges that are likely to worsen over the next few years. With a strong dependency on hydropower, renewable generation is growing from the current 0.3 GW of wind capacity to 2.4 GW by 2025, before reaching 3.6 GW by 2030. Concurrently, emerging grid-connected solar PV capacity extends to an impressive 3.3 GW by 2025 ahead of the 5.3 GW projected installed capacity [88].The electricity grid in Ethiopia is now entirely prime-moved by renewable energy sources and the Growth and Transformation Plan II (GTP II)[§§§] imply that this trend will continue [89].

The Ethiopian government aspires to diversify renewable energy generation to ensure an economically feasible and environmentally benign power sector in compliance with the country’s Climate Resilient Green Economy (CRGE)[****] strategy [69]. Even though the country’s plans are promising, there are still issues and challenges regarding demand-supply balance. These demand-supply balance challenges lead to recursive blackouts and interruptions of electricity [10].

There is a growing evidence that unearths most blackouts and outages of a power system are caused by poorly dispatched generating units [2][10]. For one, under frequency and over frequency occur due to the imbalance between generation and load as presented in Table 5-2. As it can be seen from Table 5-2, that all generating units of Fincha power station and all generating units of Amertinesh power station out aged due to under frequency[††††]. The main reason for under frequency, in turn, is demand-supply imbalance also known as power mismatch as frequency is not only a function of the speed at which the turbines turn, but also a function of energy demand a power system/grid at any given time. In this regard, providing a contingency reserve could have saved the unserved demand due to the unit based partial outages.

[§§§] Deals with the Second Growth and Transformation Plan (GTP II) (2015/16 -2019/20) The main basis of the GTP II is the country’s Vision to become a lower middle-income country by 2025. In the coming 10 years, Ethiopia's Vision is to reach the level of lower middle-income countries where democracy, good governance and social justice are maintained through people's participation. The realization of this Vision calls for creating competitive, productive and inclusive economy in all its aspects. The overarching objective of the GTP II is to sustain the accelerated growth and establish a springboard for economic structural transformation and thereby realizing the national Vision of becoming a lower middle-income country by 2025.

[****] The Climate-Resilient Green Economy (CRGE)'s vision is achieving middle-income status by 2025 in a climate-resilient green economy, outlining four pillars: Agriculture, Deforestation, Power and Transportation.

[††††] According to https://www.tandfonline.com/doi/abs/10.1080/15325008.2014.893545, the realistic and performance optimization inherent of the load frequency control (LFC) and security-constrained economic dispatch are fully considered without simplifying assumptions. For this purpose, modelling security-constrained economic dispatch as a discontinuous control action in the continuous Frequency response model of a power system is well addressed. Considering conflict behaviour of LFC and security-constrained economic dispatch beside the powerfulness of the multi-objective genetic algorithm (GA) to solve high-dimensional problems with conflicted objective functions makes it attractive for the automatic generation control coordination.

TABLE 5-2. UNIT BASED PARTIAL OUTAGES (2015-2016)

Power plant	Unit	Outage (MW)	Date and time	Reason
	UNIT I	29	22nd may 2013 at 6:03	Under frequency
	UNIT II	29	26th April 2013 at 6:00	Under frequency
FINCHA	UNIT III	29	7th October 2013 at 23:50	Under frequency
	UNITIV	16	29th November 2015 at 7:18	Under frequency
AMERTI	UNIT I	15	22nd May 2013 at 11:48	Under frequency
	UNIT II	15	13th April 2014 at 11:15	Under frequency
GIBE I	UNIT I	10	26th April 2013 at 7:06	Under frequency
	UNIT II	10	6th November 2014 at 11:11	Under frequency
	UNIT I	102	23rd January 2015 at 12:13	Over-voltage
	UNIT II	99.2	27th October 2015 at 6:00	Over-voltage
	UNIT Il	12	29th November 2015 at 23:50	Under frequency
AWASH II	UNIT II	10	7th October 2013 at 23:50	Under voltage
	UNIT I	35	7th January 2016 at 23:50	Under frequency
	UNIT II	35	22nd May 2013 at 11:48	Under frequency
MELKA	UNIT I	2.5	17th January 2016 at 23:50	Over-current
	UNIT II	2.5	29th November 2015 at 7:18	Over-current
	UNIT I	20	13th April 2014 at 11:15	Under frequency
	UNIT I	10	7th October 2013 at 23:50	Phase unbalance
ADAMA	ALL	16.4	7th October 2013 at 23:50	Lost voltage
ASHEGODA	ALL	0.64	29th November 2015 at 23:50	Lost voltage
ADAMA	ALL	14.64		Lost voltage
Total outage		704.38		

Officially, the blackout report of the Ethiopian electric power network from 2013 to 2016, reported 15 major outages. Natural incidents, equipment failure, and power mismatch, collectively known as contingencies, caused these blackouts. A contingency is an event that removes one or more generators or transmission lines from the power system, increasing the stress on the remaining network. Production plants and service centres were down for an average of four months a year [2]. This official blackout report [‡‡‡‡] supports the aforementioned argument on the prospect of employing AI based SCED of renewable generation.

[‡‡‡‡] Blackout report given to the authors in hand, there are no website-based reports on it. Even though the report is not internationally published, papers such as [2] were conducted based on this report.

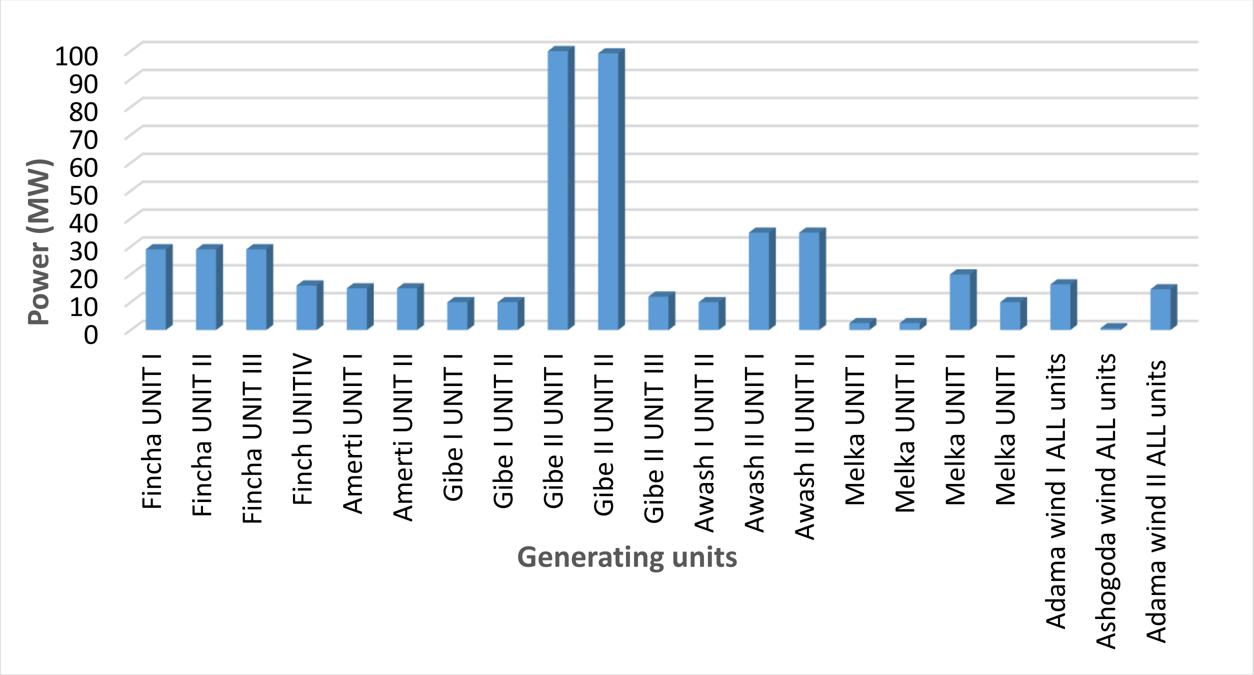


Figure 5-4. Plant-based full outages (2013)

A deeper understanding of blackouts in reference to demand-supply imbalance can be obtained from the understanding of the effects of increasing demand. If any small increase in loading demand occurs, the power demand will be greater than the supply, and the voltage will decrease. As the voltage decreases, the difference between the power supply and demand increases, consequently leading to voltage collapse.

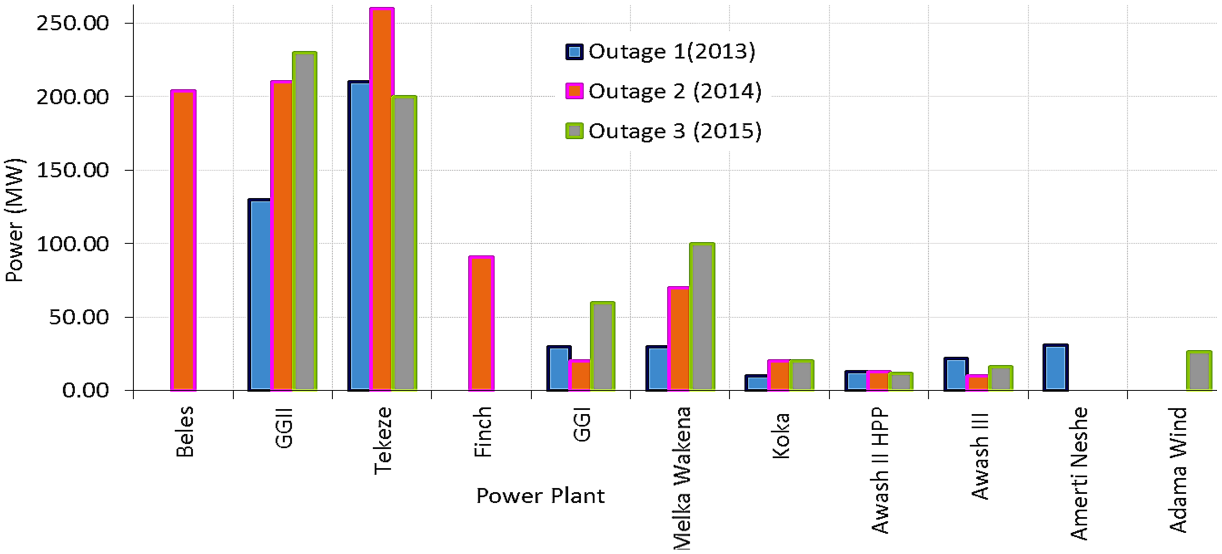


Figure 5-5. Plant-based full outages (2014)

It is well known that an excess power supply results in an overvoltage and a deficit in power supply results in an under voltage. This excess and deficit in the power supply can be produced due to disturbances and contingencies imposed on operational power systems. Thus, an equilibrium point where both the demand and supply are balanced is required.

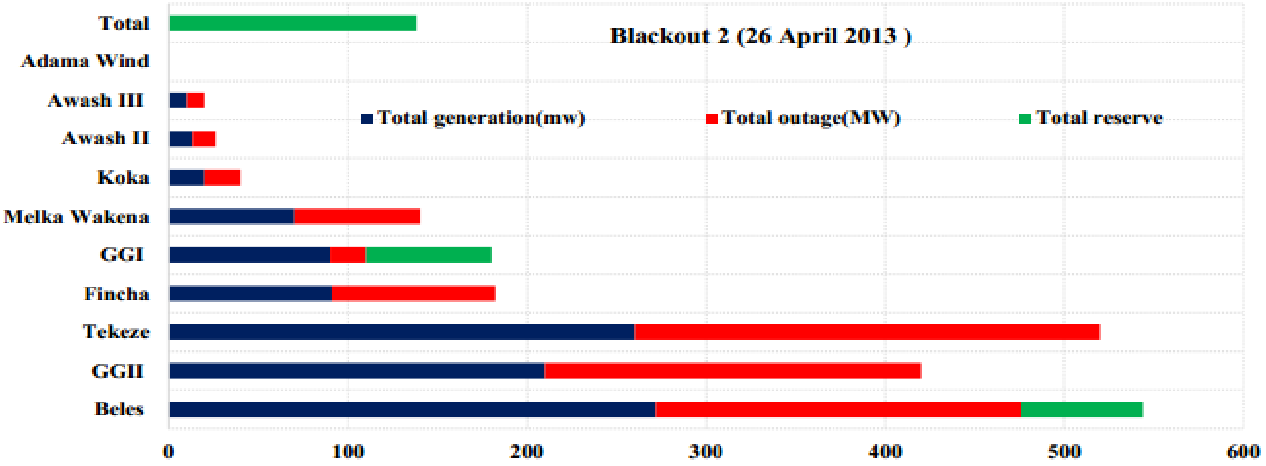


Figure 5-6. Total plant blackout samples 2013

As determining an optimal and feasible solution of different functions with conflicting objectives is a moving target, a view of power system operation that ignores SCED is short-sighted. The recursive blackouts presented in Figure 5-2 and Figure 5-3 imply that the existing Ethiopian load dispatch centre cannot deal with the challenges that the sector is facing in connection with the intermittent renewables, power imbalance, and fluctuating demand profile. Finding an optimal generation level and scheduling daily operation accordingly, is a vital task of power system operation.

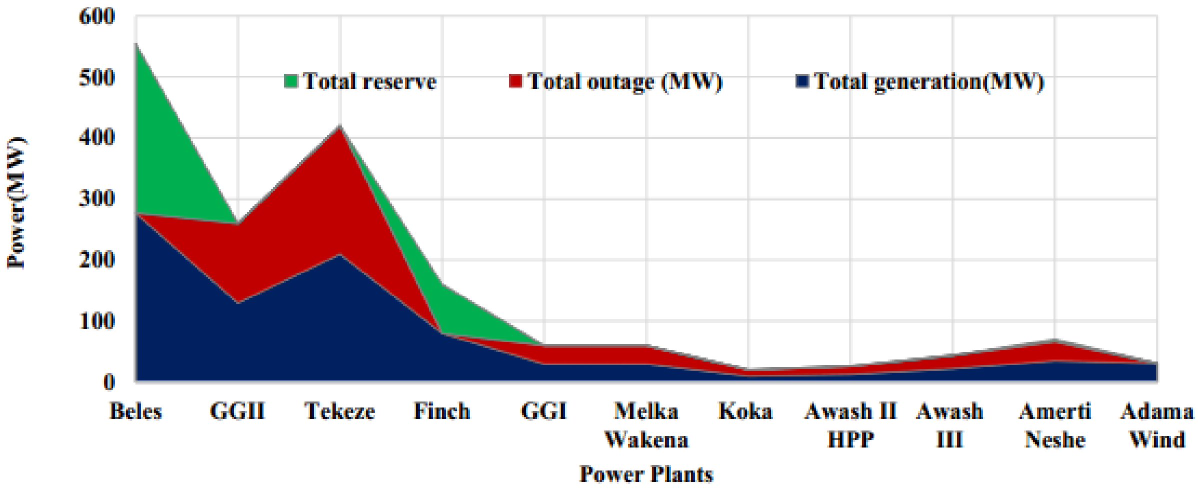


Figure 5-7. Total plant blackout samples 2015

An estimated 85% of customers who participated in an interview responded that they are sick and tired of recursive power service interruptions and blackouts during holidays, weekends and heavy rain. Holidays and weekends are when the peak demand gets high and during heavy rain is when the power system is highly prone to contingencies. This dictates that either the system is poorly dispatched or the power grid does not possess a contingency reserve for unprecedented events. The distribution generators (DG)[§§§§] in the schematic diagram of the proposed RE system, Chapter 1, can either be used as contingencies for post contingency corrective actions or as supply to peaking demand. To do this, proper economic dispatch that considers both variable generation and demand profiles should be provided. Integrating renewable energy generators without considering their economic and technical challenges leads to recursive blackouts and power service interruptions that subsequently affect the economic growth and daily socio-economic endeavours of a given community [10]. For example, in the Ethiopian power grid, day-to-day operation decision is done manually without the employment of any economic dispatch.

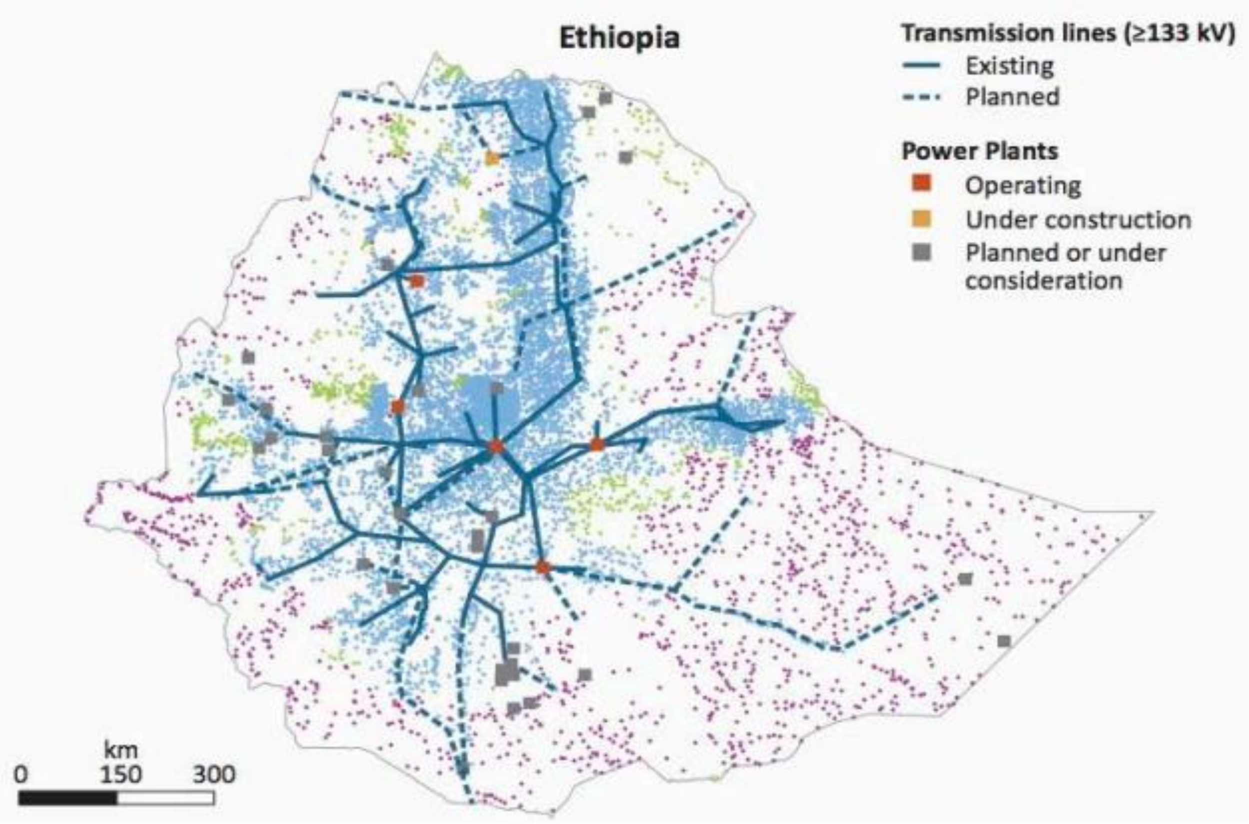


Figure 5-8. Location of existing and planned renewable generation stations

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[§§§§] Distributed generation, also distributed energy, on-site generation (OSG), or district/decentralized energy, is electrical generation and storage performed by a variety of small, grid-connected or distribution system-connected devices referred to as distributed energy resources (DER.(https://en.wikipedia.org/wiki/Distributed_generation).

Ethiopia is endowed with various renewable energy resources. The estimated potential for hydropower is 45 GW, wind is 10 GW, geothermal is 5 GW, and solar irradiation ranges from 4.5 kWh/m2/day to 7.5 kWh/m2/day [90] [70]. As of hydropower generation, large and small hydro potential estimates to 45GW, which is only 5% of the exploitable reserve. Wind potential is estimated to be 1,350 GW, less than 1% of the exploitable reserve [90].

In a comprehensive construct, several papers presented Ethiopian renewable energy resource potential assessments and prospects of integrating renewable generation. Hossain Mondale et al.[70] clearly articulated the prospects of improving energy efficiencies and mitigating greenhouse gasses emission of Ethiopian energy generation. Generation capacity of the current Ethiopian national grid, demand forecast, power mismatches and blackouts are discussed below.

a. Generation capacity

Electric power generation in Ethiopia currently depends on hydropower. At the same time, in 2012, only about 23% of the total population was connected to the national grid. The electricity grid in Ethiopia is now entirely prime-moved by renewables, and the priority projects imply that this trend will continue. Geographic access to electricity is 56% with household connectivity of 25% and per capita electricity consumptions of 100kWh/day [88] [69].

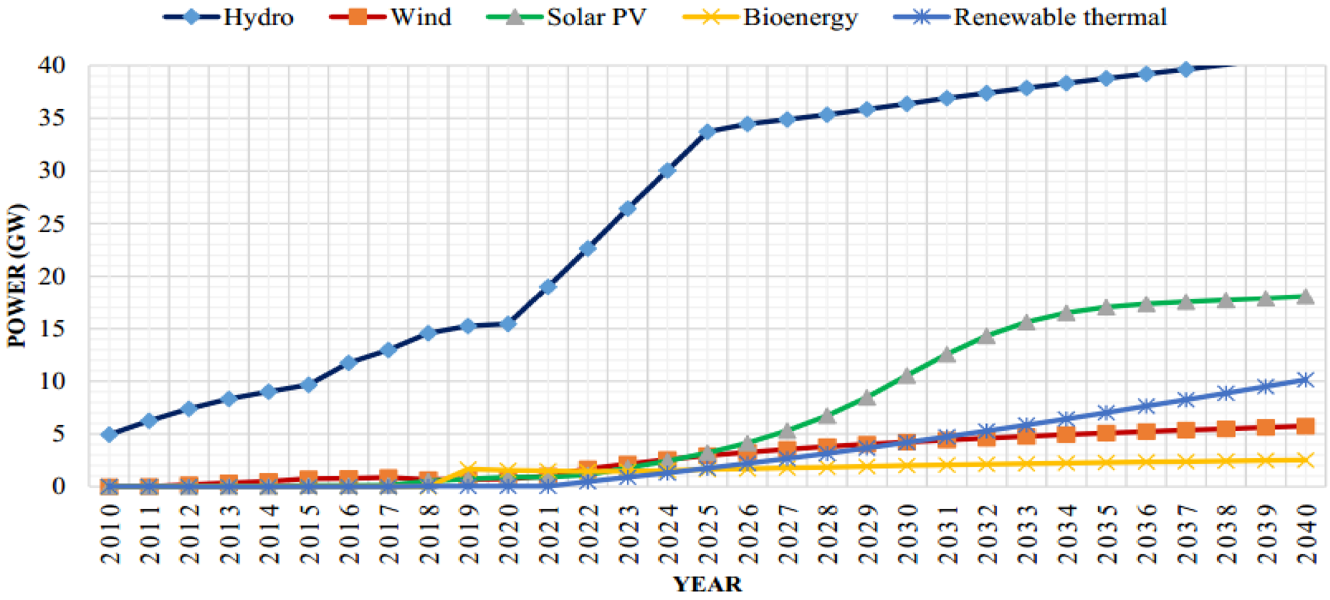


Figure 5-9. Annual forecasted generation capacity

From a comprehensive understanding of the Ethiopian power grid, 99 power plants as renewable energy systems are identified. These include 48 operational power, 16 plants under construction, and 35 planned.

Technology-wise, the planned power grid constitutes 35 hydropower plants 18 geothermal power plants, 11 wind power plants, 9 solar power plants, and 21 renewable thermal power plants. In this study, the plants that are operational and under construction were used. Hence, the considered renewable energy system constitutes 85 generating units and is dispatched for a projected year of 2025.

Figure 5-10. Ethiopian Renewable Energy systems state-of-the-art.

b. Demand forecast

The average annual growth in electricity demand from 2012 to 2013 was approximately 14% while electricity consumption per capita was 60 kW in the year 2012. According to [70], an estimated 23% population had access to electricity in 2012. Ethiopia faces a significant challenge while working to achieve sustainable development. Economic growth, population growth, and industrialization greatly increase electricity demand [89].

In response to these challenges, the Ethiopian Electric power (EEP)***** is executing many projects in consideration of demand for electricity to enhance its capacity in line with the growth of the country. The electricity demand has doubled for the past 10 years and is expected to increase by 28% -32% per year in the next five years. The plan for GTP II is to reach the capacity of power generation 17.3 GW (up to about 5 GW in 2016) and 21,728 km of transmission lines by 2020 [69]. These figures do not signify the effect of variable demand, recursive blackouts and intermittent generation. Both intermittent renewable generation and variable demand depend on weather conditions.

Demand profile also depends on the type of customers. Most electric grids and utilities serve different customers of different sectors such as residential, commercial, and industrial. The electric usage is not the same for customers that belong to different sectors but somewhat similar for customers within the same sector [83]. Even though it is a bit challenging to forecast hourly demand exactly, the figure below presents the peak demand forecast of ERES for the coming 17 years. It can be seen from the forecast that the energy demand increases as the country’s economic growth expedites.

***** Ethiopian Electric Power (Amharic: ኢትዮጵያ ኤሌክትሪክ ኃይል) is an Ethiopian electrical power industry and state-owned electric producer. It is engaged in development, investment, construction, operation, and management of power plants, power generation and power transmission. The company is a main key in the Ethiopian energy sector.

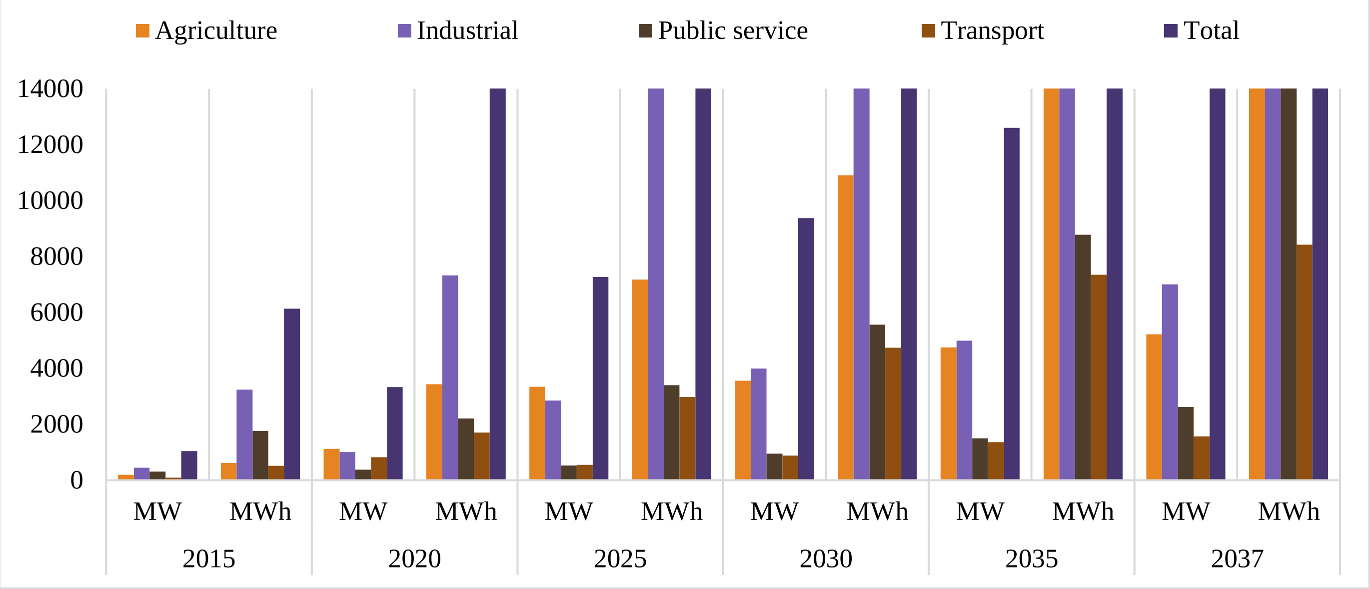


Figure 5-11. Sector-wise demand forecast

To cope up with the growing demand's pace, intensive study on-demand profiles, accurate short term planning, load forecast, the demand-supply balance should be provided. The prospects of empowering a skilled workforce, advancing the weak institutional capacity and providing economic and regulatory framework are recommended.

c. Power Mismatch

To dispatch a power system, it is imperative to study supply and demand profiles. Supply refers to the existing generation capacity of the power system while demand refers to the load of the grid. Ethiopia has a final energy consumption of around 40,000 GWh, whereof domestic appliances consume 4%, the transport sector consume 3%, and the industry consumes 92% [15]. An outage is deviation of an intermittent renewable source from its fluctuated value, which leads to generation-load mismatch also known as power mismatch. This induces frequency deviation and activates contingency reserves of the power system.

In a smart and properly managed grid, Distribution Generators (DG) can be used as contingency reserves. Before dispatching DG, it is imperative to understand their generation capacity, capacity factor and Levelized Cost of Energy (LCOE). Knowing generation capacity helps to make sure that the unserved demand due to contingencies and be satisfied. Selection of either base-load or peak lead is done based on capacity factor and LCOE[†††††] helps to prioritize plants with low generation cost.

[†††††] Cost can be measured in many ways, and each way of accounting for the cost of power generation brings insights. The costs that can be examined include equipment costs (e.g. wind and hydropower turbines, PV modules, solar reflectors), replacement costs, financing costs, total installed cost, fixed and variable operating and maintenance costs (O&M), fuel costs and the levelised cost of energy (LCOE)

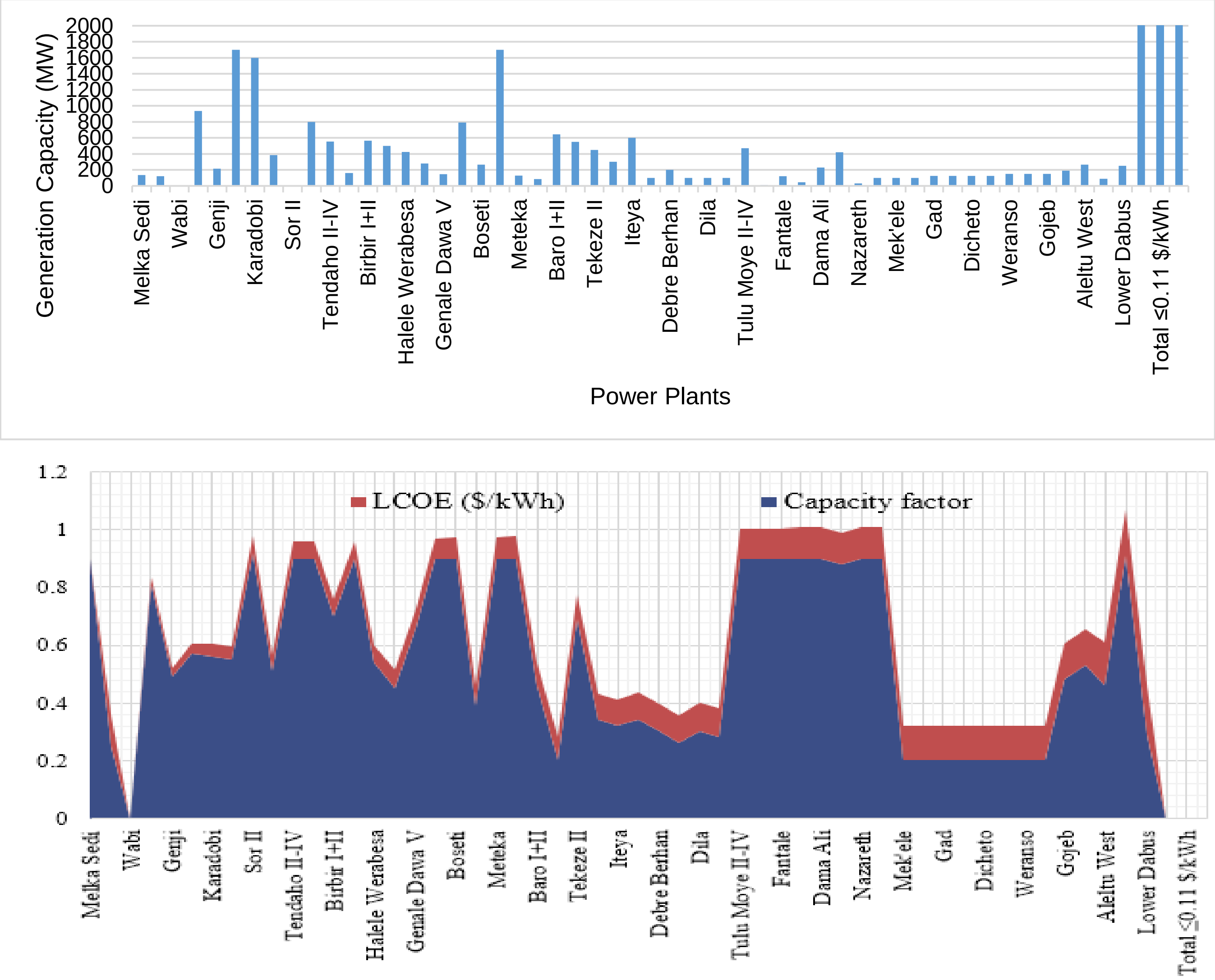


Figure 5-12.Capacity factor, generation capacity and LCOE

In light of this, matching the diverse characteristics of renewable energy sources to the widely varying rural needs is facilitated by employing integrated renewable generation. Integrating renewables without considering their economic and technical challenges lead to recursive blackouts and power service interruptions that subsequently affect the economic growth of the country [14]. Ethiopia’s current grid is inadequately maintained, and grid quality and stability are already matters of concern, making the integration of renewables a heightened challenge. Employing computationally efficient SCED can overcome these challenges.

For example, with large reservoirs, hydropower can store energy over weeks, months, seasons or even years. Hydropower can therefore provide a full range of ancillary services (spinning reserve, non-spinning reserve, operating reserves, responsive reserve, regulation up, and regulation down) required for high penetration of wind and solar [21].

To do this, definite and accurate dispatch interval, dispatch level and reserve allocation are needed. The operator needs to know when to dispatch the hydropower generation unit instead of solar power generating unit or wind power generating unit. This inquiry can be fulfilled using SCED. This way, the so-called ‘duck curve’ challenge of solar PV generation can be solved.

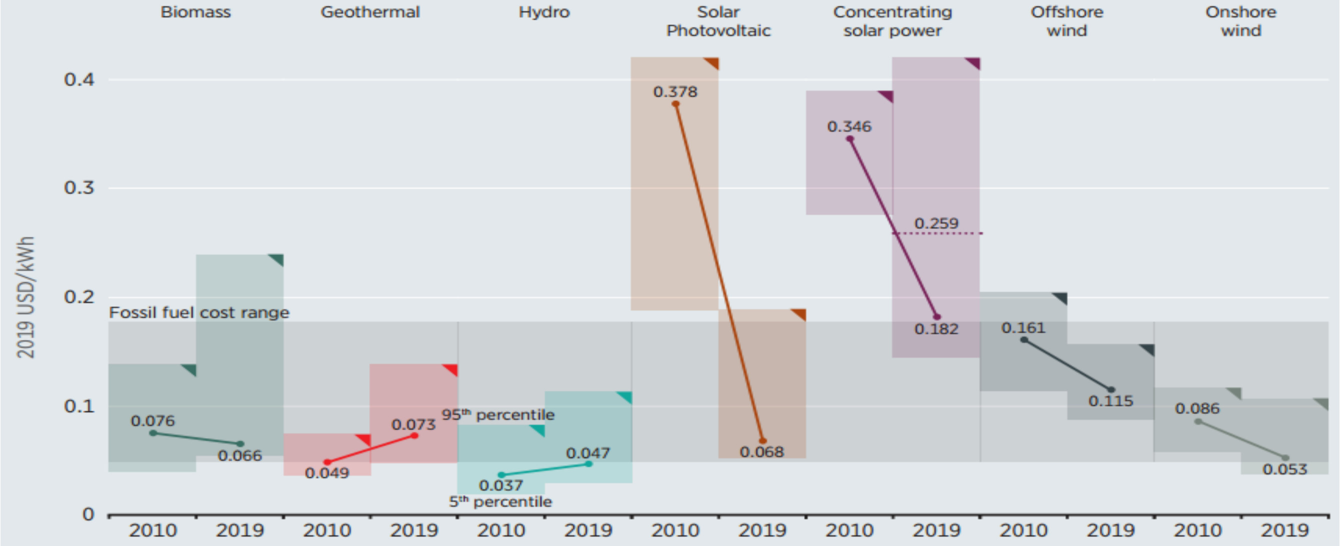


Figure 5-13. Renewable power generation costs in 2019 [91]

TABLE 5-3 SOURCES OF DATA

Test system	Data source	Ref.	Details
Modified New England 39-Bus System	- Illinois center for a smarter electric grid(ICSEG), - Dynamic IEEE test systems, - Electric grid test repository,	[17]	- https://icseg.iti.illinois.edu/ieee-39-bus-system/, - https://www.kios.ucy.ac.cy/testsystems/index.php/dynamic-ieee-test-systems/ieee-39-bus-modified-test-system, - https://electricgrids.engr.tamu.edu/electric-grid-test-cases/new-england-ieee-39-bus-system/
NREL IEEE-118 bus system	- NREL: transforming energy - Electric grid test repository - U.S. Department of Energy Office of Scientific and Technical Information	[82]	- https://www.nrel.gov/news/program/2016/21643.html - https://electricgrids.engr.tamu.edu/electric-grid-test-cases/ieee-118-bus-system/ - https://www.osti.gov/biblio/1416258-extended-ieee-bus-test-system-high-renewable-penetration.
Ethiopian renewable energy system*	- Energypedia - Export gov	[2]	- https://energypedia.info/wiki/Ethiopia_Energy_Situation - https://www.export.gov/article?id=Ethiopia-Energy

Chapter 6. Results and Discussions

6.1. Results

6.1.1. MVMO based SCED Results for Modified New England 39 bus system

The results of SCED for RES obtained from DIGSILENT power factory and MATLAB are presented below.

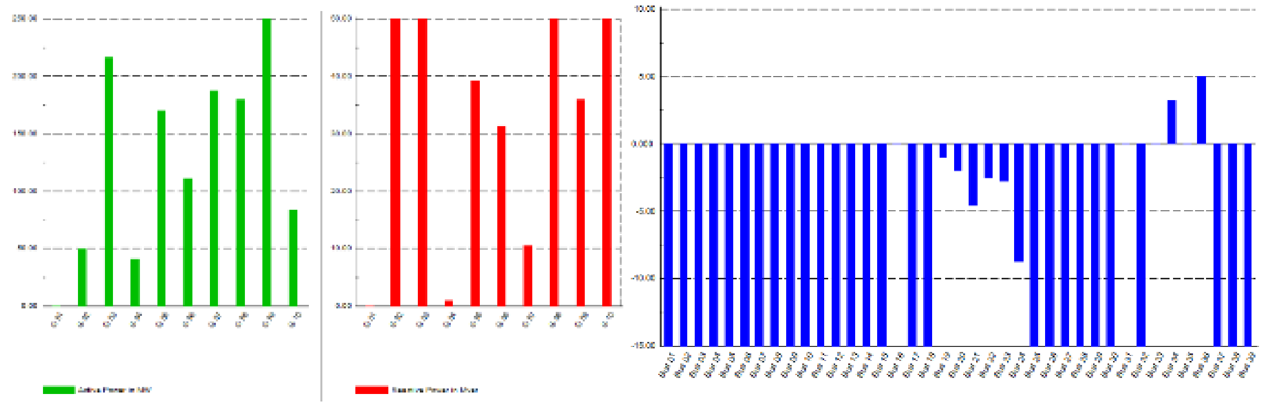


Figure 6-1. Active and reactive power dispatch, voltage and power angle deviation of New England 39 Bus system with no RES

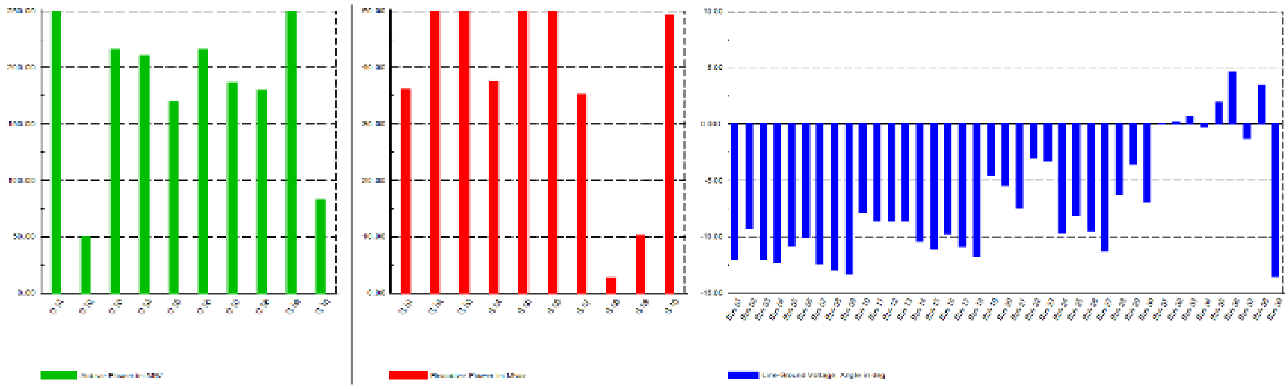
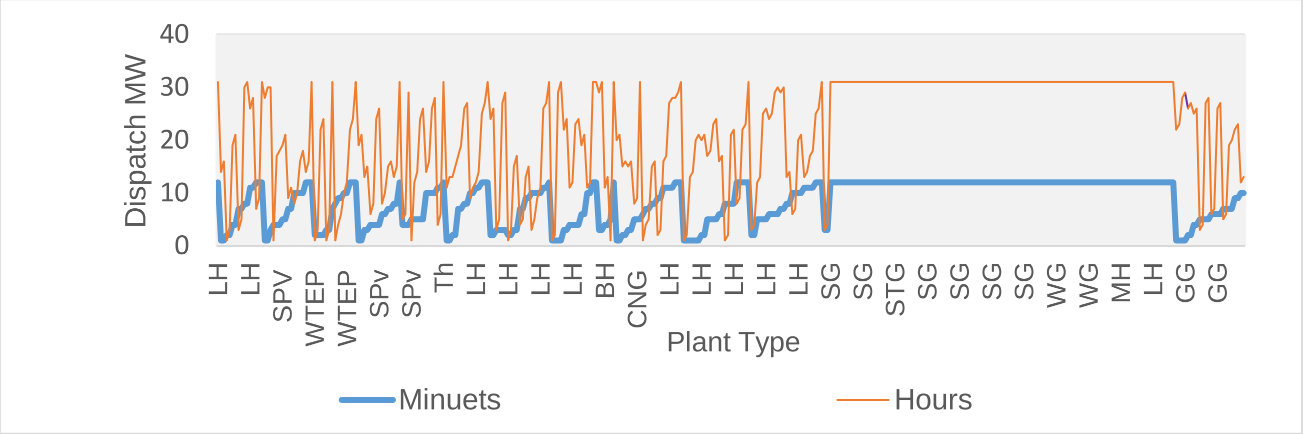
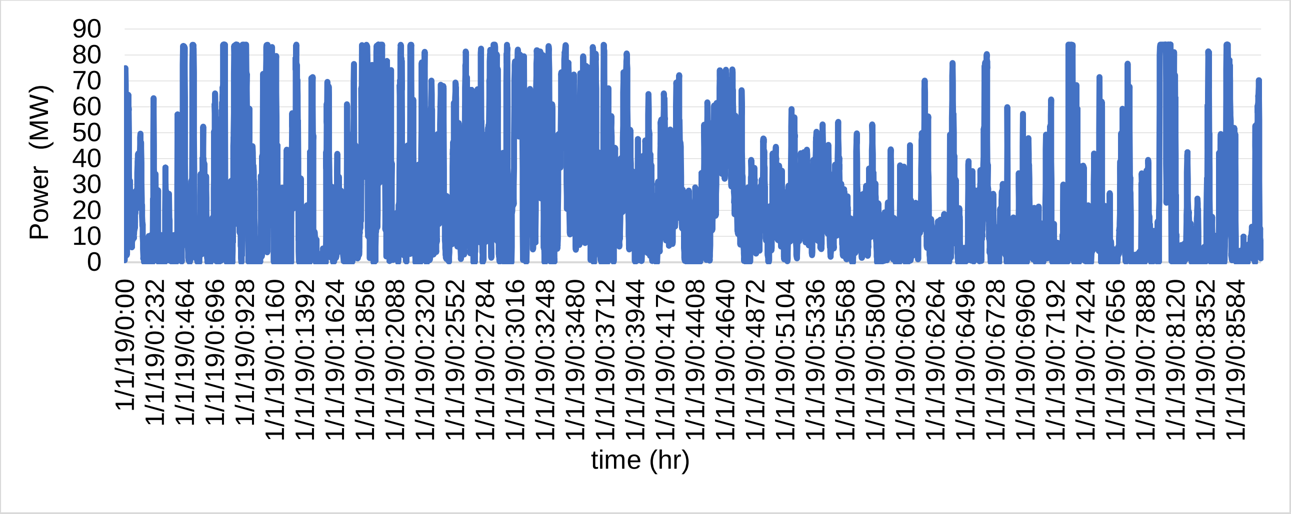


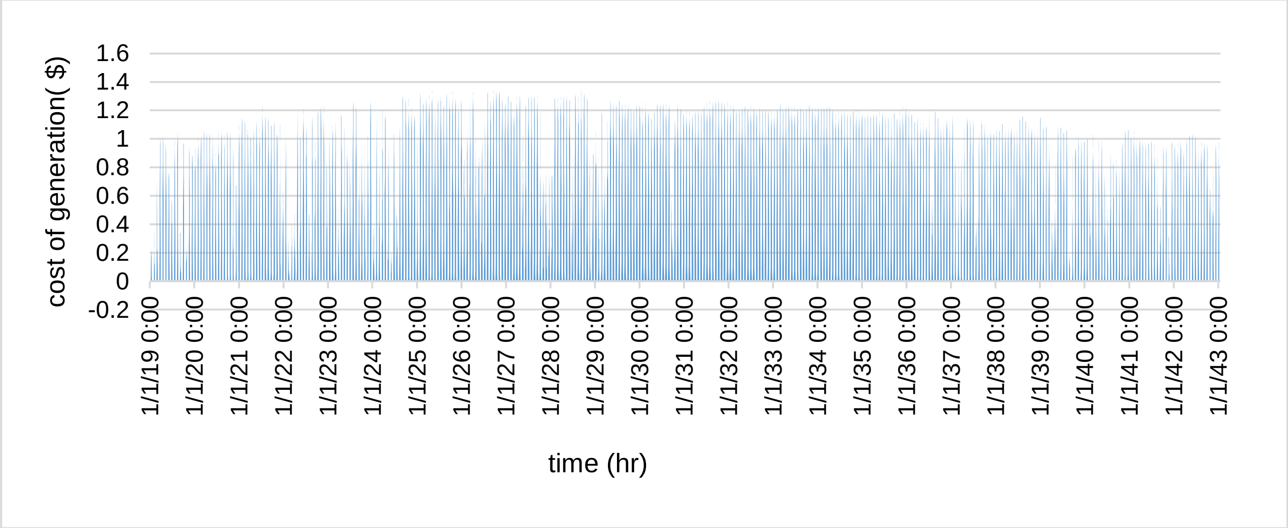
Figure 6-2. Active /reactive power dispatch, voltage & power angle deviation of modified New England 39 Bus system with RES

Figures 6-1 and 6-2 present the effect of RES penetration to a conventional New England 39 bus system. Dig silent for identifying the challenges posed to power grid due to renewables entry is used. It clearly shows the effect of RE penetration on the demand-supply affecting the power angle and voltage. This part of the study is challenging to carry out on MATLAB. Figures 6-3 and 6-4 depict the energy share of RES including which type of energy address which dispatch and time it takes to complete the task. The power dispatch challenges such as duck curve can be overcome using RES.





(a)



(b)

Figure 6-3. (a).Generation dispatch of Ethiopian renewables and (b) Generation cost of Ethiopian energy systems

Figure 6-5 presents cost of energy generation per kWh in properly regulated energy markets and power dispatch of Ethiopian power system of selected renewable energy conversion technologies.

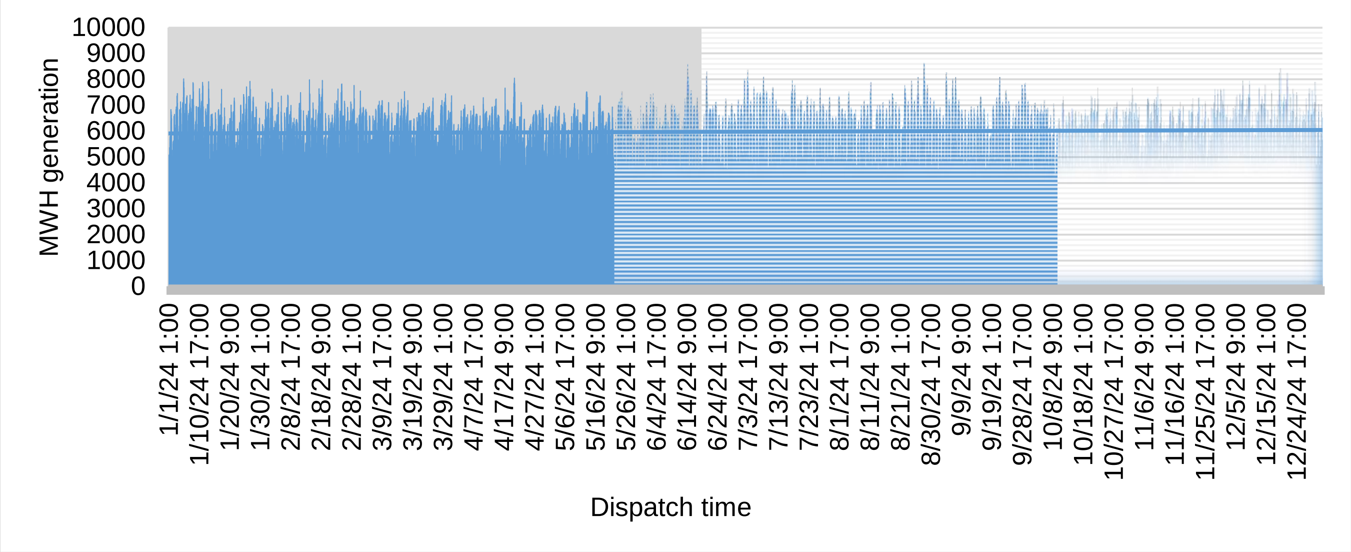


Figure 6-4. Daily MWh generation dispatch

Figure 6-4 presents the total MWH dispatch of the RESs for NREL 118 bus system. Electrical energy is typically sold to consumers in kilowatt-hours. The cost of running an electrical device is calculated by multiplying the device's power consumption in kilowatts by the operating time in hours, and by the price per kilowatt-hour.

The unit price of electricity charged by utility companies may depend on the customer's consumption profile over time. The economic dispatch concept begins by turning on /dispatching a generating unit with the lowest operational costs. Increase the generation unit’s capacity output until all load is met or the generating unit reaches its capacity constraint, whichever comes first.

If the cheapest generating unit reaches its capacity constraint before all the demand is met, the second-cheapest generating unit is turned on, and increases power until either it reaches its capacity constraint or all the demand is met. The process continues by successively turning on more generators that are expensive until the entire load is served. It is important to realize that the economic dispatch algorithm does not consider any fixed costs of power plants - only those costs directly associated with plant operation.

TABLE 6-1.MULTI-VARIABLE MULTI-OBJECTIVE SIMULATION RESULTS

Gen	Plant Type	MVMO solution	Gen	Plant Type	MVMO Solution
1	Hydro	12.65	34	Solar	12.16
4	Hydro	11.28	36	Wind	10.3
6	Hydro	17.84	40	Wind	14.18
8	Hydro	21.38	42	Wind	15
10	Hydro	258.86	46	Geothermal	75
12	Hydro	95.76	49	Hydro	110
15	Solar	15	54	Solar	40.82
18	Solar	15	55	Wind	13.14
19	Wind	12.5	56	Geothermal	14.52
24	Wind	10	59	Hydro	157.26
25	Hydro	289.98	61	Thermal	41.92
26	Hydro	421.8	62	Wind	11.82
27	Waste	13.7	65	Hydro	400
31	Thermal	43.1	66	Hydro	120.
32	Biomass	11.02	69	Hydro	525
	Cost ($/hr)	1279.1762		Cost ($/hr)	1601.26
	P_{Loss}(MW)	14.382		P_{Loss}(MW)	19.605

Table 6-1. Presents the results of selected generating units comprising different types of plants. Indicating where the RES are situated, it also shows the economic cost and power transmission loss considering credible contingencies and uncertainties

6.1.2. EPGA based SCED Results

The following figures depict the simulation results including the behaviors of a particular genetic algorithm.

TABLE 6-2. COMPARISON TABLE BETWEEN SOLUTION METHODS

Unit Generation (MW)	Newton Raphson	MVMO solution	EPGA solution
P1	450	450	450
P2	325	324.66	322.85
P3	200	200.38	201.98
Power mismatch (Mw)	0	$-4.6\text{x}10^{-5}$	$-4.6\text{x}10^{-5}$
Cost($/hr)	8236.25	8236.20	8236.18
Run time (sec)	0.2	0.125	0.105

A dispatch comparison between different solution methods of example 3.1.with a 3 unit fixed generation supplying a fixed demand before they are used for ERES is presented in Table 6-2. Execution time and production cost of the system solved using EPGA is less than that of conventional methods. This comparison was done to indicate the robustness of EPGA. Practical interpretation of the mathematical frameworks for renewable generation are also discussed.

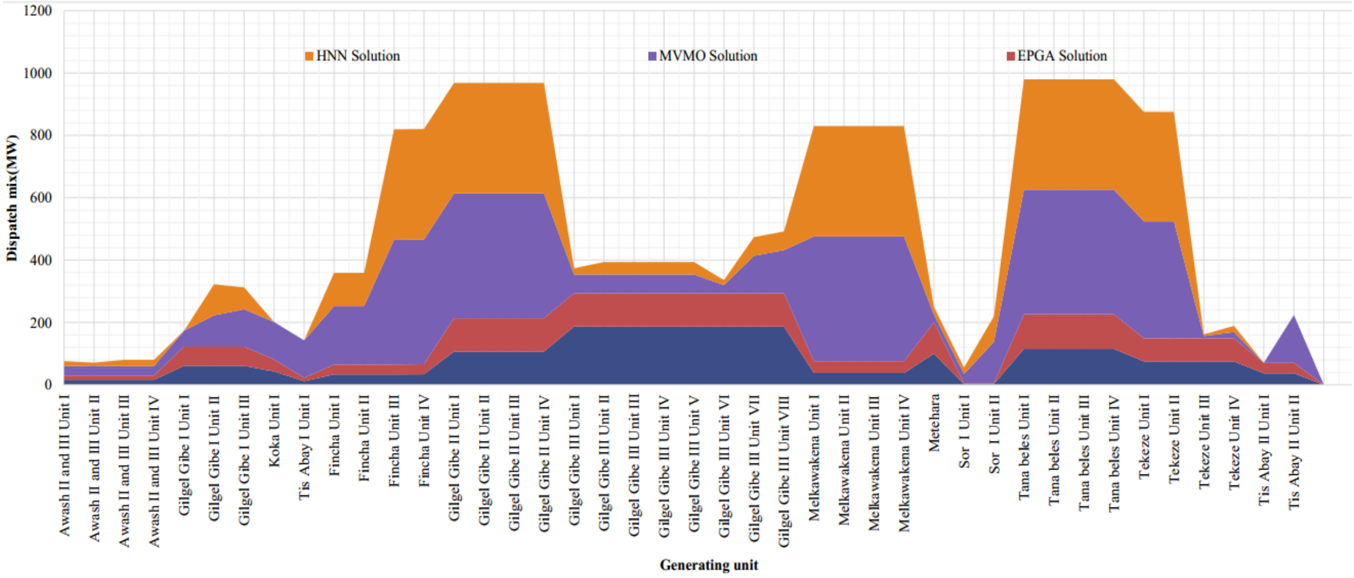


Figure 6-5. Dispatch contribution and generation share of considered generating units

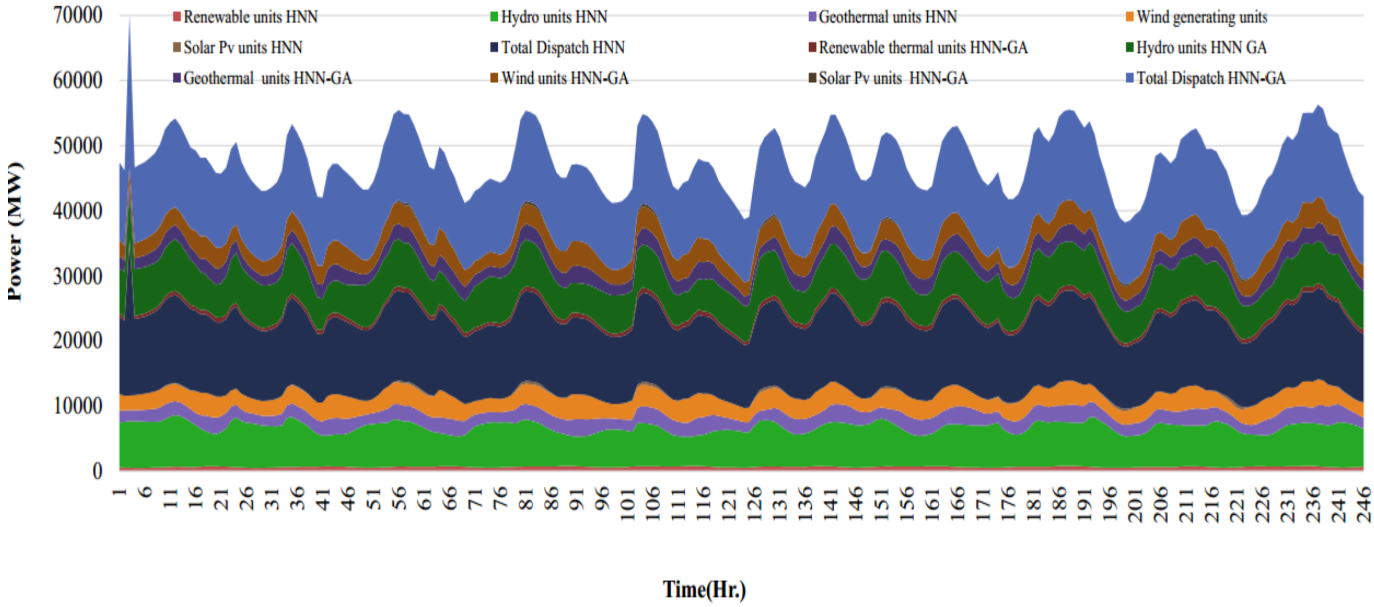


Figure 6-6. Total dispatch over a week

The dispatch and generation share of considered generating units presented in Figure 6-5 serves a peak demand. The dispatch result is imperative in verifying if the output of the objective function satisfies the design constraints and operational limits. SCED is carried out daily as depicted in Figures 6-6 and 6-7.

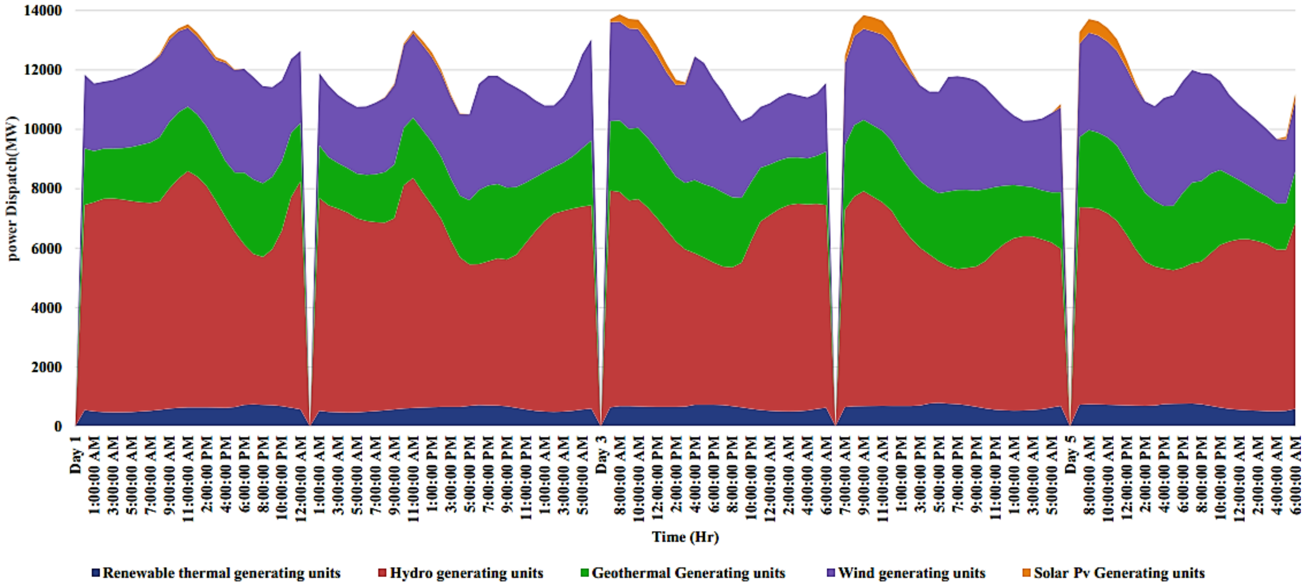


Figure 6-7. Five-days power generation dispatch

Short-term operation and planning being SCED’s input deals with day-to-day operations of the power system. Ethiopia has a long-term plan of 20 years horizon mainly dependent on hydropower capacity with no consideration on an integrated dispatch of renewable generation. As of short-term operation and planning, the existing national dispatch center visualizing real-time operation and major transmission lines is not fully functional. Accurate and short term load forecasting can help to estimate load flows and to make a decision that can prevent overloading. Timely implementation of such decisions leads to the improvement of network reliability, security and reduced occurrences of blackouts.

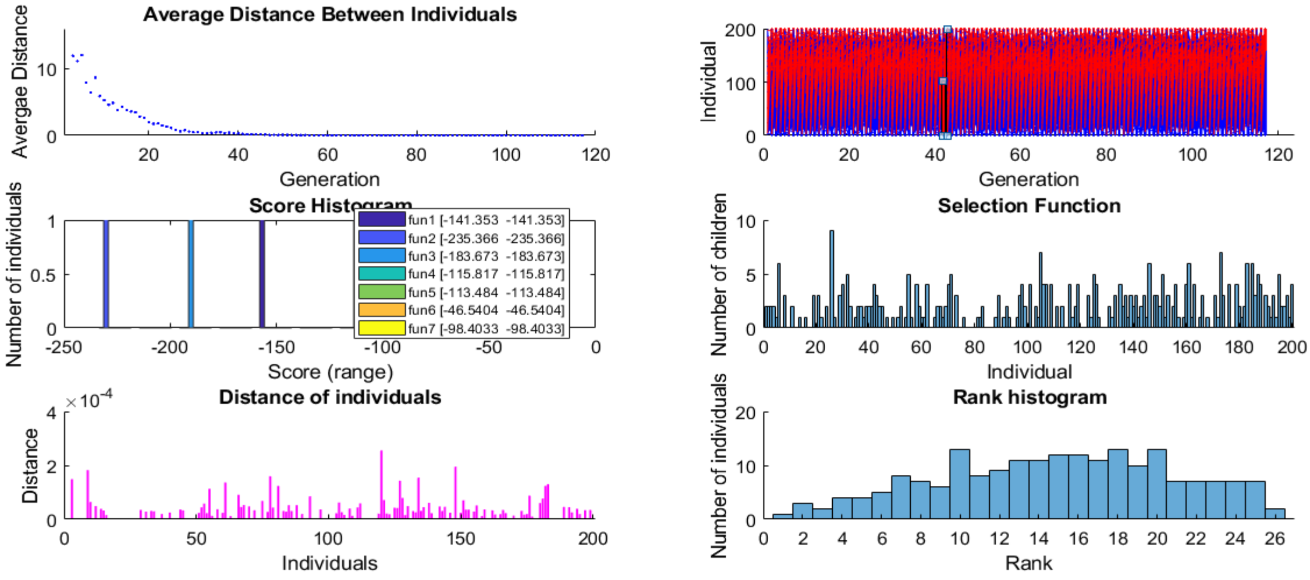


Figure 6-8. Results showing EPGA features and properties

With supply and demand fluctuating, intermittency of weather conditions and dramatic changes in energy prices during peak demand, a computationally advanced SCED solution method such as EPGA is imperative. The simulation result in Figure 6-9 shows the feasibility and effectiveness of the proposed computational method in providing alternate dispatch to reduce conflicting objectives like optimal power output, least cost and high security.

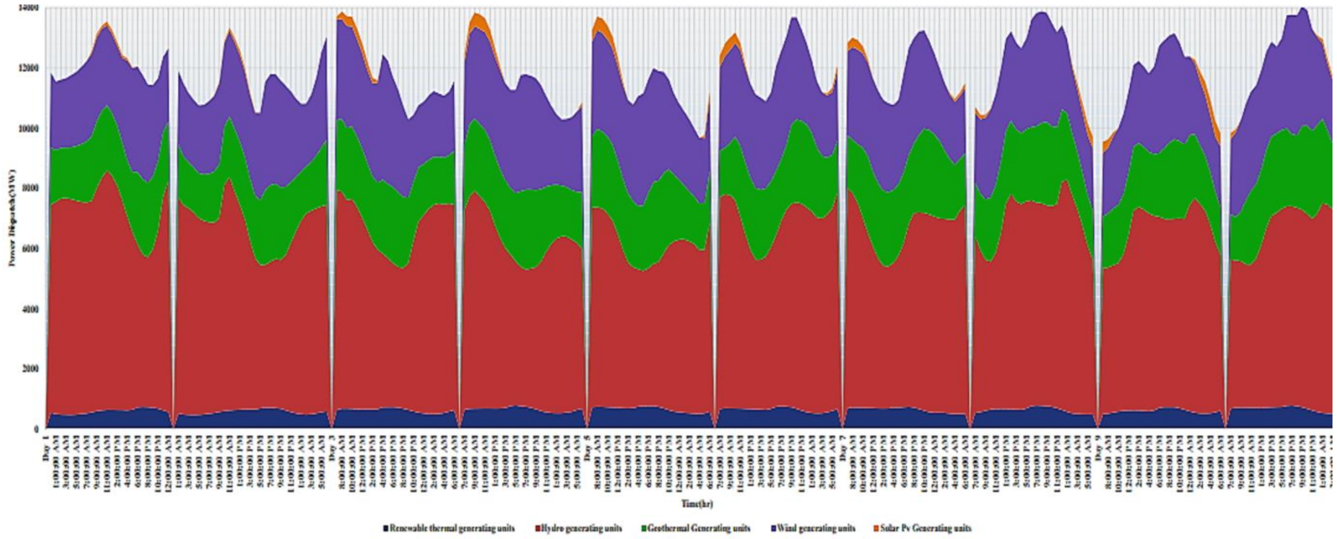
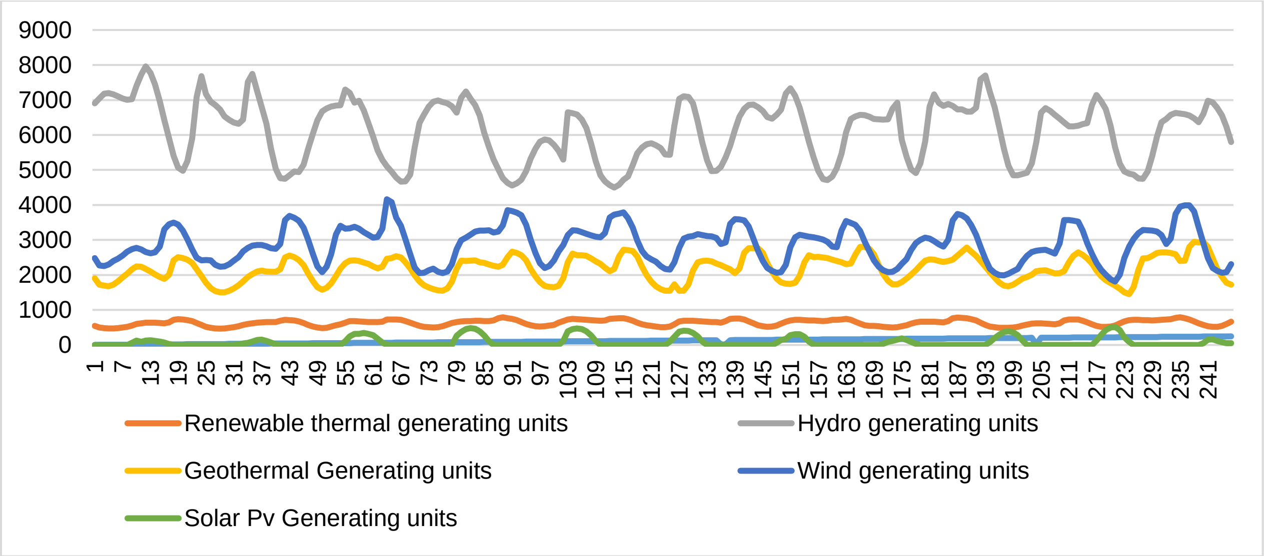


Figure 6-9. Ten-days power generation dispatch

There is an important difference in load between weekdays and weekends. Furthermore, Mondays and Fridays being adjacent to weekends can have structurally different loads than Tuesday through Thursday. Day and night also, have a different share of load and generation effects. Figure 6-10 thus helps to grasp the effect of weekend demand profiles on SCED of ERES.



(a)

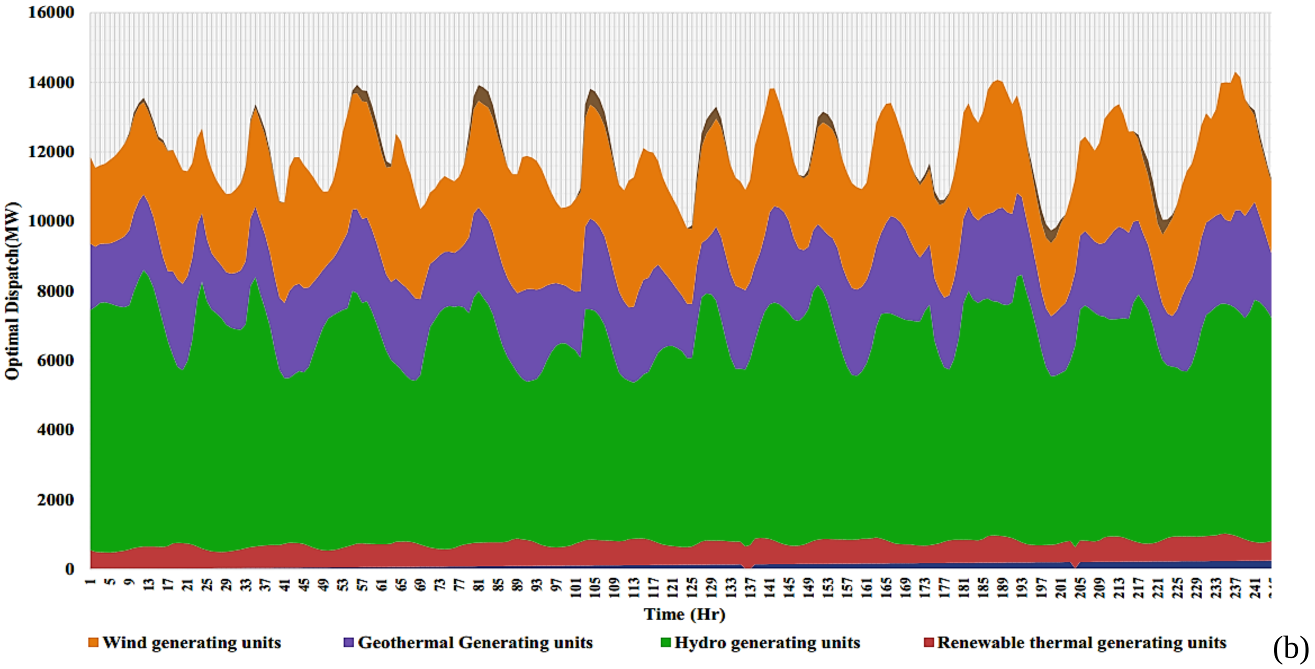


Figure 6-10. Optimal weekly power dispatch (a). Addressing ‘duck curve’ of solar PV dispatch (b). Improving overall system security

If a power system has excess generation at any instant then the frequency will increase. By contrast, if there is an insufficient supply of electricity to meet demand at any time then the system frequency will fall. If it falls too far, the power system will become unstable. To get the system back to normal operation, the operator needs to dispatch reserves, in which their cost was taken in to account at the critical economic operation of power systems stage as shown in Figure 6-11. It is worth to notice that the generating units that possess a dispatch pattern that can be easily predicted can be used as base loads. For example, hydro generating units can be used as base loads. However, as every hydropower station has different generation cost, hydropower with the lowest generation cost should be called on first.

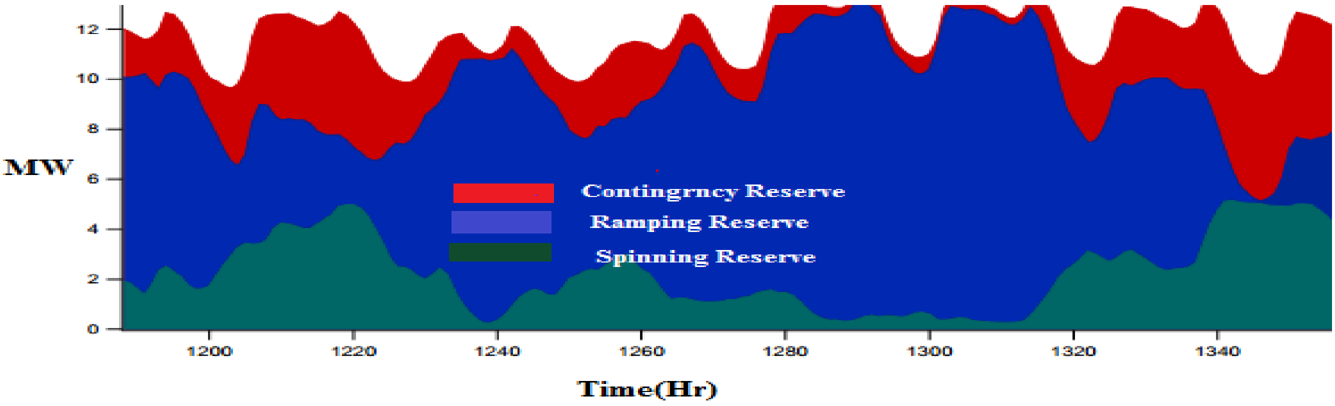


Figure 6-11. Reserve and contingency allocation results

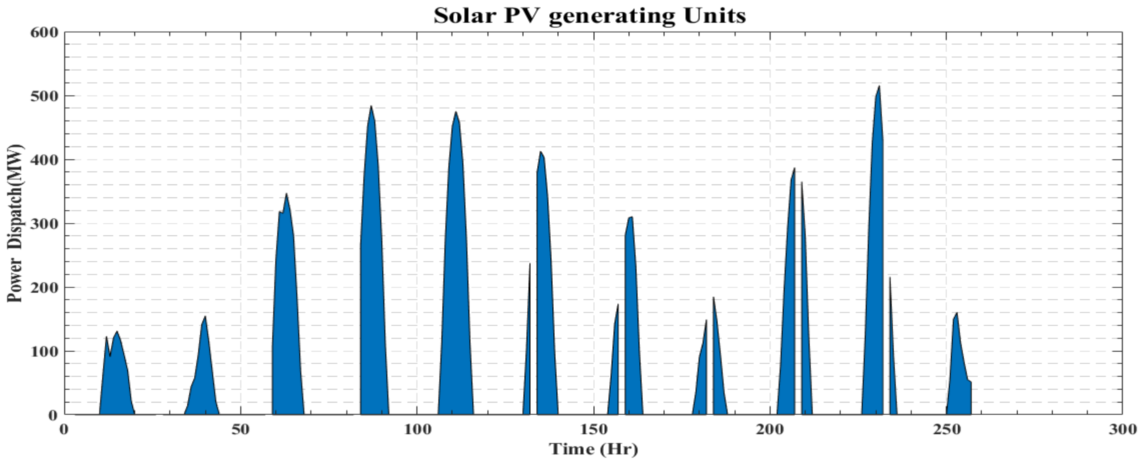


Figure 6-12. Dispatch share of solar PV units

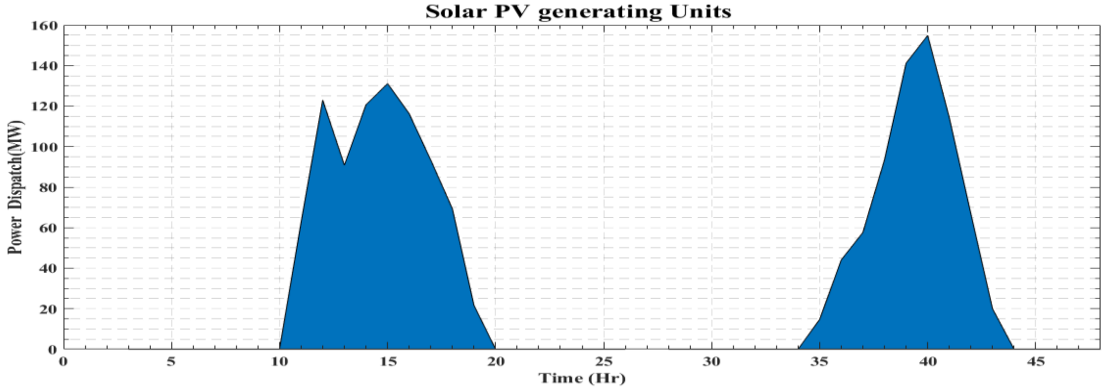


Figure 6-13. Two days dispatch share of solar PV units

TABLE 6-3.TWO DAYS DISPATCH OF ERES

Time (Hr)	Renewable thermal units	Hydro units	Geothermal units	Wind units	Solar PV units	Total Dispatch
1	546.7296	6908.483	1904.445	2486.384	0	11847.04155
2	499.5382	7045.734	1726.221	2273.633	0	11547.12606
3	482.9468	7175.419	1694.141	2256.416	0	23394.16761
4	474.9739	7201.357	1679.883	2301.918	0	11662.1314
5	473.2475	7164.612	1726.221	2399.07	0	11768.15114
8	482.1889	7106.254	1817.709	2460.559	0	11866.71086
7	504.0089	7040.33	1936.525	2554.022	0	12034.88594
8	522.4075	7003.586	2032.766	2661.012	0.0197079	12219.79114
9	554.7832	7021.958	2164.651	2739.718	62.82363031	12543.93396
10	596.0196	7399.127	2241.881	2770.462	122.9885806	13130.47914
11	622.5524	7722.261	2232.376	2729.88	90.85627255	13397.92534

12	637.691	7958.937	2169.404	2653.634	120.6441083	13540.30971
13	640.6281	7773.054	2096.926	2619.2	131.1142355	13260.92285
14	636.7224	7446.679	2017.32	2642.566	116.26645	12859.55294
15	631.3324	6957.115	1941.278	2808.586	93.34304056	12431.65383
16	622.4717	6426.485	1885.434	3309.105	69.32081069	12312.81593
17	646.6324	5898.015	2003.062	3448.069	21.67234823	12017.45115
18	721.2445	5408.452	2415.352	3496.031	0	12041.07891
19	736.383	5064.785	2513.969	3441.92	0	11757.05716
20	724.5716	4977.247	2483.077	3268.522	0	11453.41733
21	712.7245	5254.99	2435.551	3021.337	0	11424.6024
22	681.7838	5901.257	2344.063	2727.42	0	11654.52416
23	625.5703	7088.962	2164.651	2488.844	0	12368.02728
24	569.0832	7684.436	1967.417	2421.206	0	12642.14203
25	521.1653	7165.693	1779.688	2427.355	0	11893.90157
26	487.5789	6951.712	1627.604	2415.057	0	11481.95197
27	473.0861	6858.77	1537.304	2287.16	0	11156.32106
28	466.7589	6730.165	1502.848	2234.28	0	10934.052
29	472.0368	6531.314	1506.412	2245.348	0	10755.1109
30	490.0004	6425.404	1551.562	2306.837	0	10773.80323
31	510.6903	6360.561	1618.099	2410.138	0	10899.48836
32	536.2232	6319.494	1706.023	2510.98	14.70451345	11087.42382
33	569.0832	6436.211	1815.333	2674.54	44.12590314	11539.29299
34	600.3288	7514.764	1944.842	2774.152	57.62119002	12891.70769
35	616.871	7749.279	2029.201	2840.56	93.47696888	13329.38761
36	634.1081	7254.312	2100.491	2861.466	141.1942989	12991.57055
37	641.8881	6804.734	2127.818	2860.236	154.9081194	12589.58508
38	655.3317	6315.171	2094.55	2820.883	114.2320676	12000.16783
39	652.1524	5612.707	2088.609	2769.233	66.77828193	11189.47913
40	654.0402	5030.202	2085.045	2743.407	19.94187384	10532.63584
41	688.5459	4764.346	2162.275	2888.521	0	10503.68776
42	715.8052	4744.893	2500.899	3569.817	0	11531.41496
43	707.5902	4849.723	2554.366	3687.876	0	11799.55483
44	701.0702	4954.552	2509.216	3637.455	0	11802.29333
45	677.1516	4937.26	2423.669	3548.911	0	11586.99218
46	624.0053	5153.403	2279.902	3353.377	0	11410.68723
47	570.3253	5597.577	2043.459	3010.269	0	11221.63003
48	525.071	6040.67	1820.086	2597.064	0	10982.89028

6.1.3. HNN base SCED Results

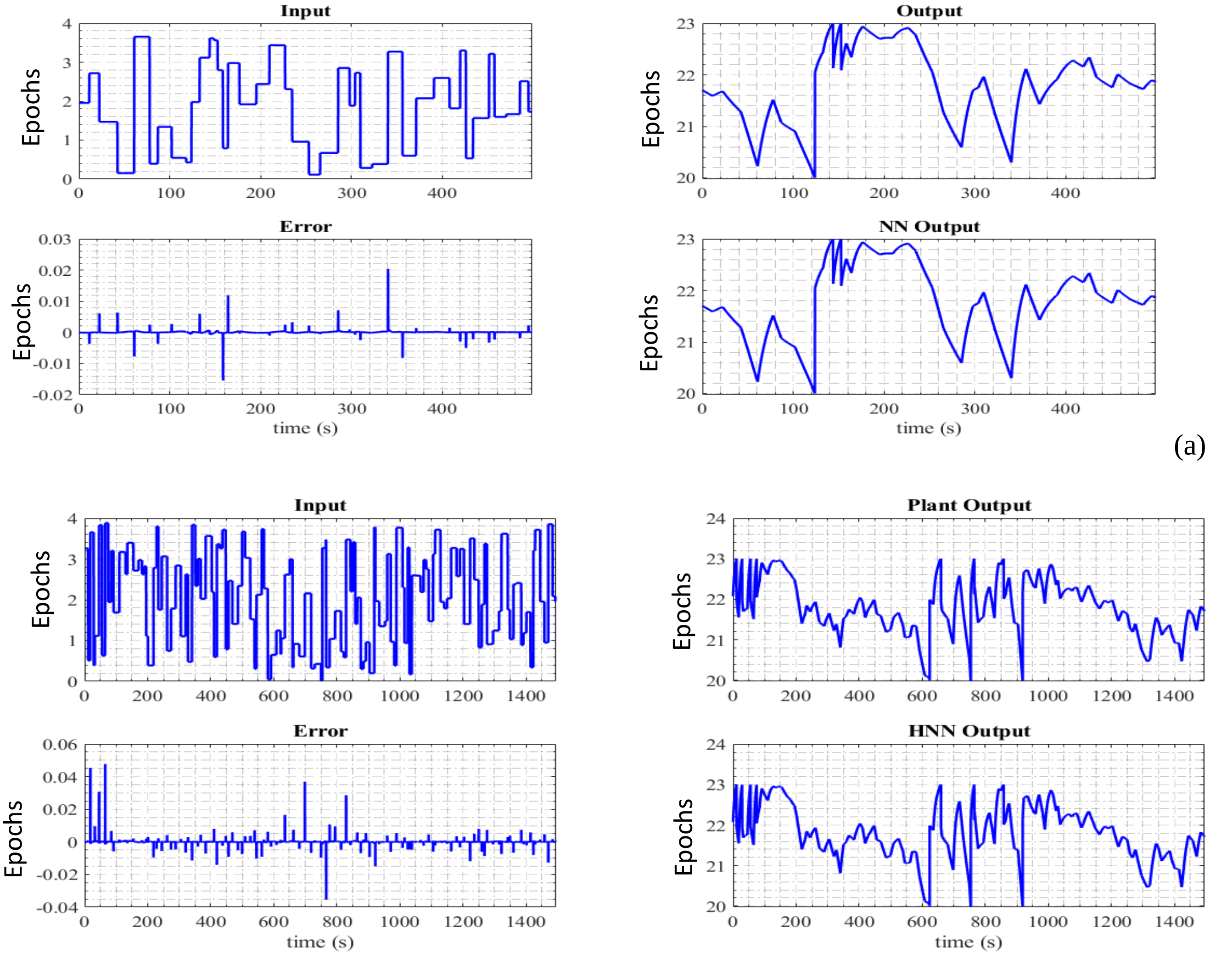
The following figures depict the simulation results including the behaviors of a particular Hopfield Neural Network.

TABLE 6-4. COMPARISON TABLE BETWEEN SOLUTION METHODS

Generation (MW)	Newton Raphson	MVMO solution	HNN solution
P1	450	450	450
P2	325	324.66	322.85

P3	200	200.38	201.98
Pm (Mw)	0	-4.6×10^{-5}	-4.6×10^{-5}
Cost($/hr)	8236.25	8236.20	8236.18
Run time (sec)	0.2	0.125	0.105

A dispatch comparison between different solution methods of example 3.1 with a 3 unit fixed generation supplying a fixed demand is presented in Table 6-4. The execution time and production cost of the system solved using HNN is less than that of conventional methods. This comparison was done to indicate the robustness of HNN.



(a)

(b)

Figure 6-14. Predictive control of variable renewable energy resources using neural networks for theNREL-118 test system (a) and Ethiopian renewable energy systems (b).

Predictive control enables the Hopfield net to lower the energy state that the net should remember. This way the net can recover from a distorted input to a trained state that can withstand contingencies as shown in Figure 6-16. Based on the errors shown in Figure 6-16, contingencies with higher error value are selected as credible contingencies for training. From this result credible contingencies can be identified.

TABLE 6-5. COMPARING MVMO AND HNN SIMULATION RESULTS

Time	Renewable thermal units	Hydro units	Geothermal units	Wind units	Solar PV units	Total Dispatch
1	546.7296	6908.483	1904.445	2486.384	0	11847.04
2	499.5382	7045.734	1726.221	2273.633	0	11547.13
3	482.9468	7175.419	1694.141	2256.416	0	23394.17
4	474.9739	7201.357	1679.883	2301.918	0	11662.13
5	473.2475	7164.612	1726.221	2399.07	0	11768.15
8	482.1889	7106.254	1817.709	2460.559	0	11866.71
7	504.0089	7040.33	1936.525	2554.022	0	12034.89
8	522.4075	7003.586	2032.766	2661.012	0.019708	12219.79
9	554.7832	7021.958	2164.651	2739.718	62.82363	12543.93
10	596.0196	7399.127	2241.881	2770.462	122.9886	13130.48
11	622.5524	7722.261	2232.376	2729.88	90.85627	13397.93
12	637.691	7958.937	2169.404	2653.634	120.6441	13540.31
13	640.6281	7773.054	2096.926	2619.2	131.1142	13260.92
14	636.7224	7446.679	2017.32	2642.566	116.2665	12859.55
15	631.3324	6957.115	1941.278	2808.586	93.34304	12431.65
16	622.4717	6426.485	1885.434	3309.105	69.32081	12312.82
17	646.6324	5898.015	2003.062	3448.069	21.67235	12017.45
18	721.2445	5408.452	2415.352	3496.031	0	12041.08
19	736.383	5064.785	2513.969	3441.92	0	11757.06
20	724.5716	4977.247	2483.077	3268.522	0	11453.42
21	712.7245	5254.99	2435.551	3021.337	0	11424.6
22	681.7838	5901.257	2344.063	2727.42	0	11654.52
23	625.5703	7088.962	2164.651	2488.844	0	12368.03
24	569.0832	7684.436	1967.417	2421.206	0	12642.14
Total	14346.24	162629.5	49594.32	65979.51	829.0492	305175.9
Pmax	736.383	7958.937	2513.969	3496.031	131.1142	23394.17
Pmin	473.2475	4977.247	1679.883	2256.416	0	11424.6
Ploss (MW)	423.5	8502	1235	4325.36	2501	1700.86
Total Cos ($/Kwh)	265401	1814782.5905	421551.72	791754.12	9932.009416	3303421.439916

Table 6-5. Compares the multi-variable multi-objective solution and HNN solution of committed power plants for the NREL- 118 test system selected zones of operation. The 'units' column describes generator type and unit designation. As can be seen from the table, generating units with 0-unit commitment value are not displayed on the table. To practically interpret the results, unit commitment input, forecasted data evaluated by predictive control of HNN, the number of recursive blackouts, and demand profile are integrated within the proposed SCED solution. From weight positions plotted in Figure 6-17, the attractor pattern on the final state, penalty function weights, and adaptive calculation of weighting factors can be obtained.

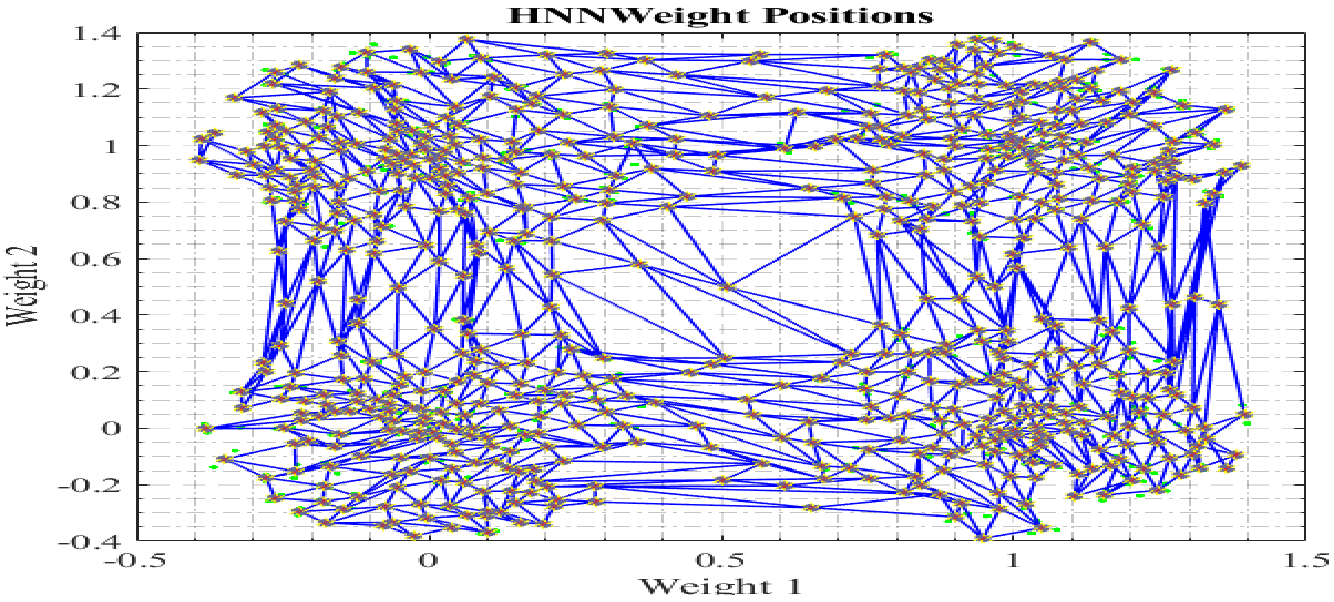


Figure 6-15. Weight positions of created HNN

Figure 6-15. Depicts weight positions and network architecture of the HNN created using ‘newhop’ command. As HNN trains and learns from feedback, every input is connected with every output.

Figure 6-16. Time series response of training the created HNN

The simulation results of the HNN including the training targets, training outputs, errors, responses, and validation are presented in Figure 6-16. In this study, errors and result fluctuations are considered as dispatch losses due to contingencies. This consideration helps in allocating contingency reserves. Based on the errors obtained from the time series response of training the created HNN, credible contingencies are identified for constraint formulation.

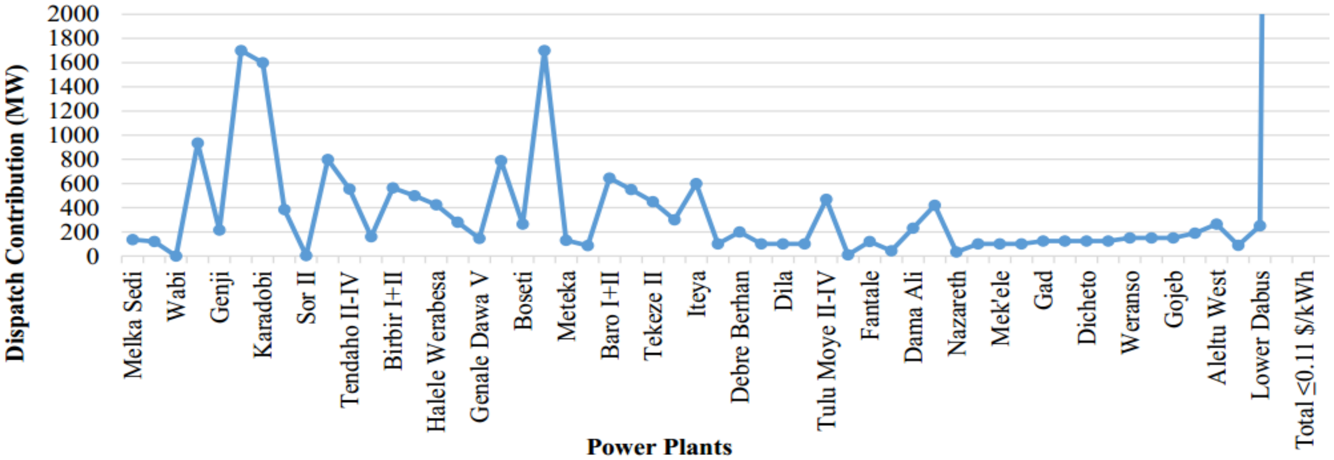


Figure 6-17. Dispatch contributions from Ethiopian existing power plants

SCED is important for scheduling when/which generator to dispatch, determining how much reserve is need for spinning, standby, ramping, and contingency. Figure 6-17 presents dispatch contributions from Ethiopian existing power plants participated in alleviating the recursive blackouts.

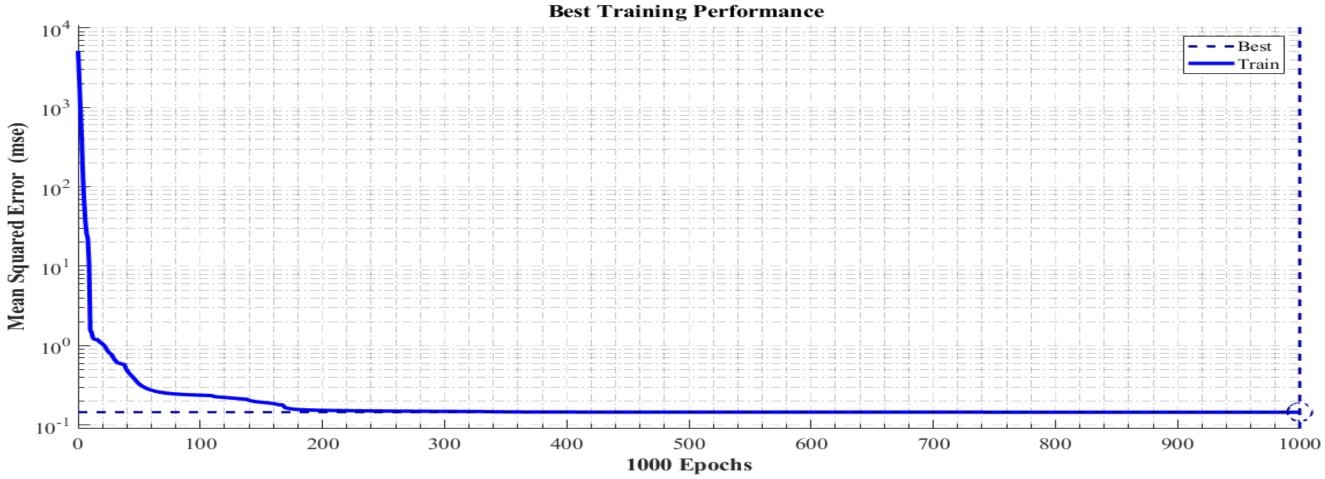


Figure 6-18. Best HNN training performance

As it is indicated in Figure 6-18, the energy function of HNN representing the whole SCED problem is stabilizing and converging as the number of iterations increase. Staring from epochs 300, the best performance is attained.

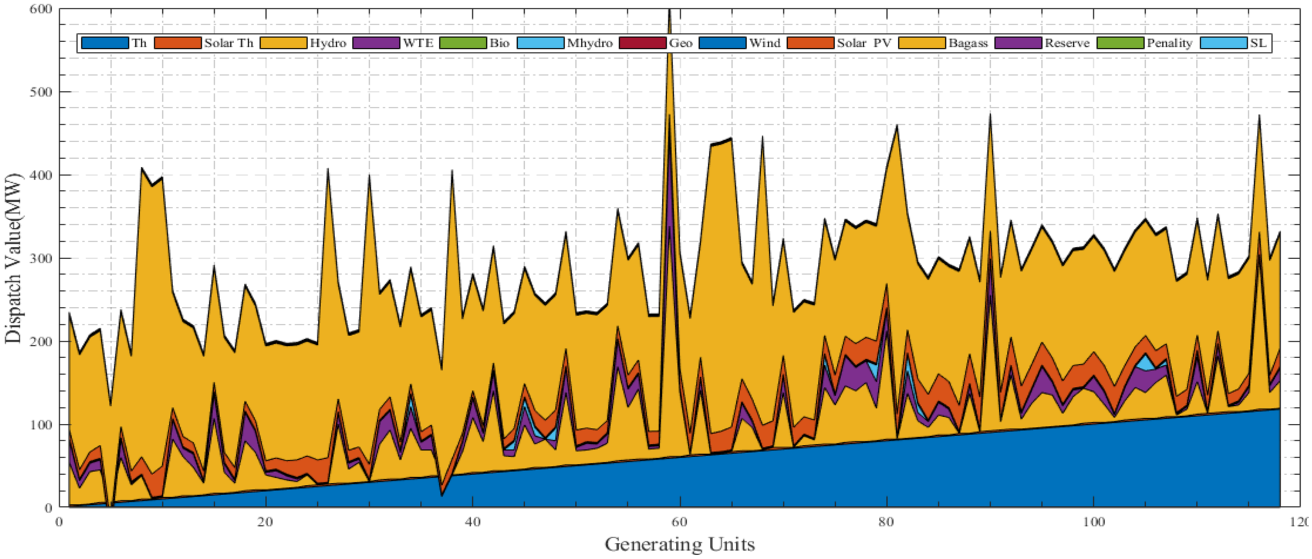


Figure 6-19. Dispatch value of generating units by technology

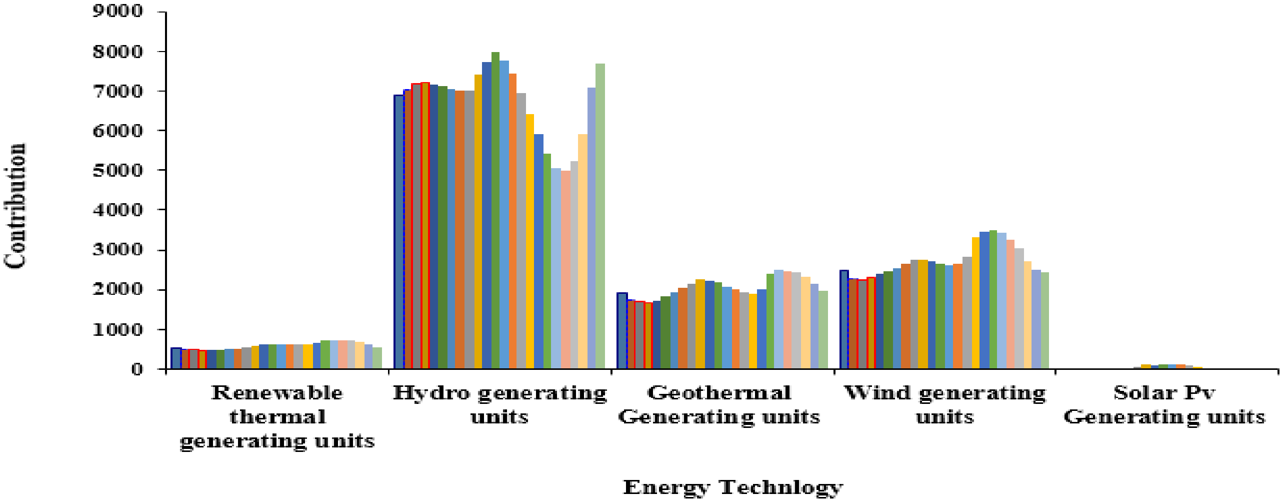


Figure 6-20. Dispatch value of NREL 118 bus system

NREL 118 test system provides a researcher the privilege of choosing and editing renewable penetrated zones based on their resemblance to a particular project. Accordingly, Figure 6-19 presents the dispatch share of renewable generation technologies and Figure 6-20 depicts ERES adopted from NREL 118 test system zones 2&3. There is an important difference in load between weekdays and weekends. Furthermore, Mondays and Fridays being adjacent to weekends can have structurally different loads than Tuesday through Thursday. Day and night also, have a different share of load and generation effects. Figure 6-21 thus helps to grasp the effect of weekend demand profiles on SCED of ERES.

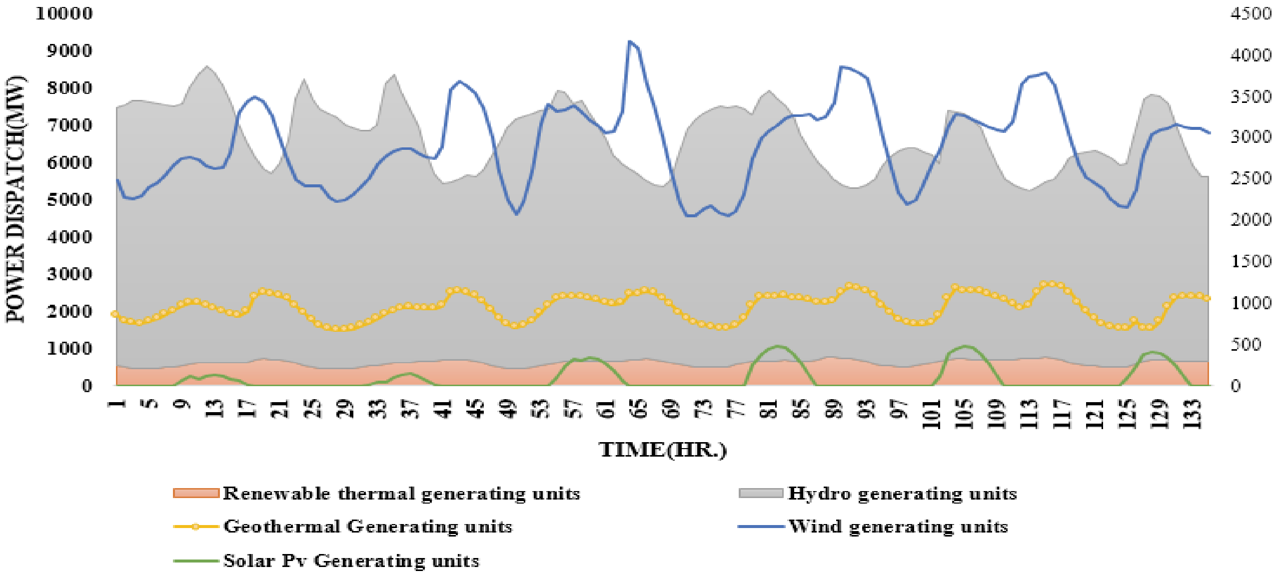


Figure 6-21. SCED results of Ethiopian renewable power plants with complete and public data

In Ethiopia, the weather does not significantly vary throughout the year, apart from solar PV generation. Therefore, demand seasonality on the grid is minimal. Here, the residential demand is characterized by lighting, cooking, and heating and since the peak is in the evening, their contribution to the system peak is significant.

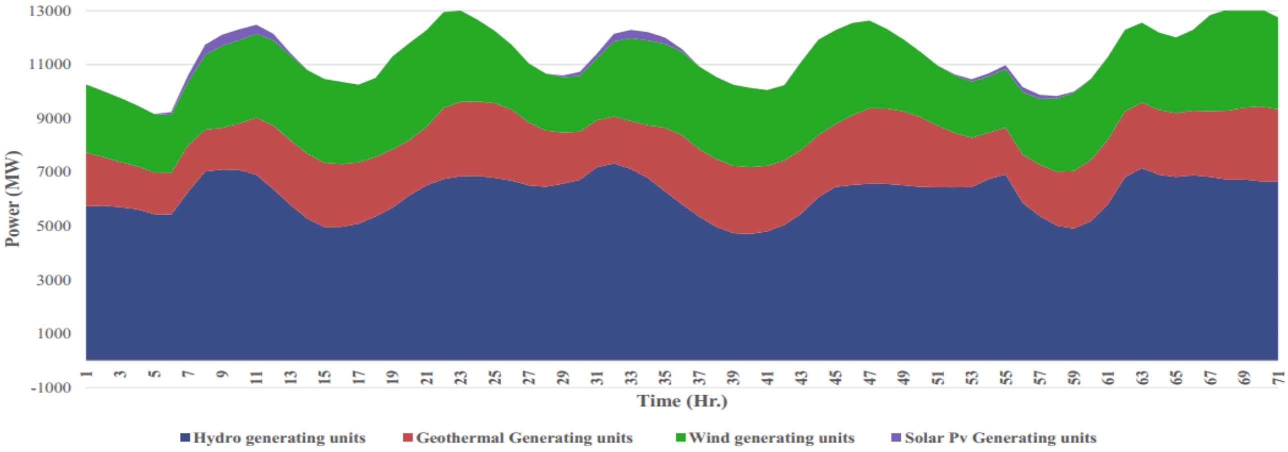


Figure 6-22. Power Dispatch MW share of Ethiopian generating units

The composition of the load is a bit different from the state cities' commercial and public services as large infrastructure, industries, schools, and hospitals operate mainly between 8:00 Am and 6:00 Pm. Additionally, the country's suburbs largely consist of small shops, hotels, bars, cafés, and restaurants that stay open throughout the evening. Available data is used to understand SCED and the dispatch contribution of each generating unit. Figures 6-21 and 6-22 depict energy share and dispatch of each Ethiopian generating unit committed so far to supply 10.023GW of power.

6.1.4. GA-HNN based SCED Results

The results of optimal SCED for RES using GA-HNN approach obtained from MATLAB are presented below.

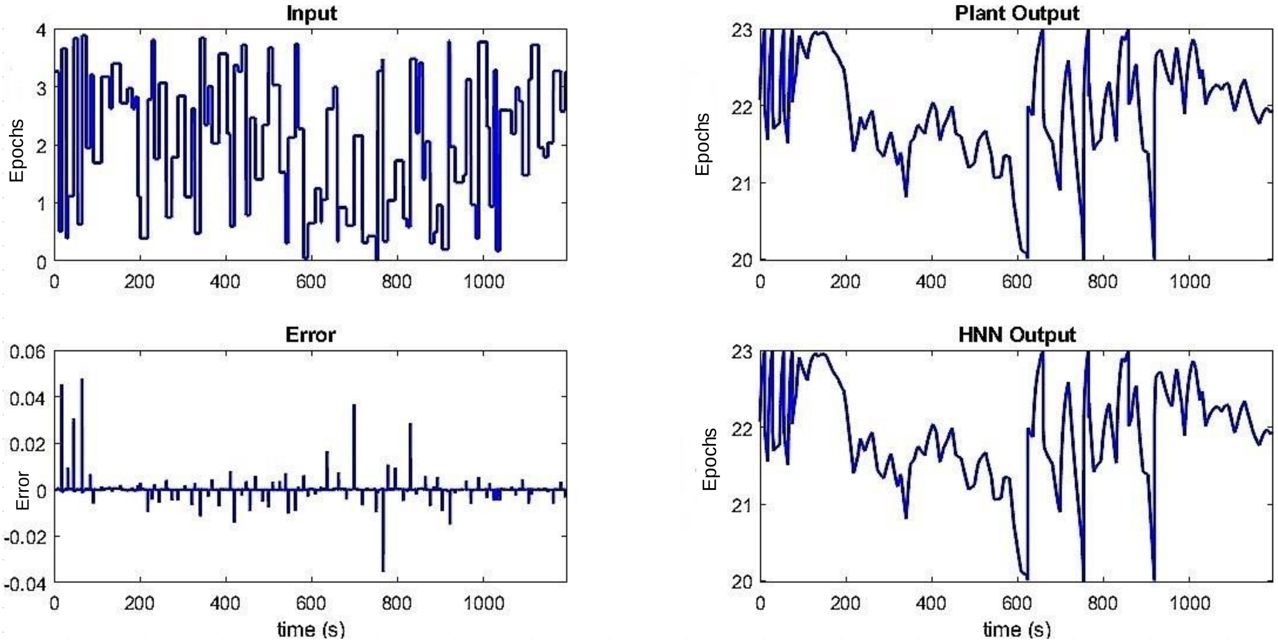


Figure 6-23. Predictive control of variable resources using neural networks in compliance to Weibull PDF

Predictive control enables the GA-HNN to lower the energy state that the net should remember. This way the net can recover from a distorted input to a trained state that can withstand contingencies as shown in Figure 6-23. Based on the errors shown in Figure 6-23 contingencies with higher error value are selected as credible contingencies for training.

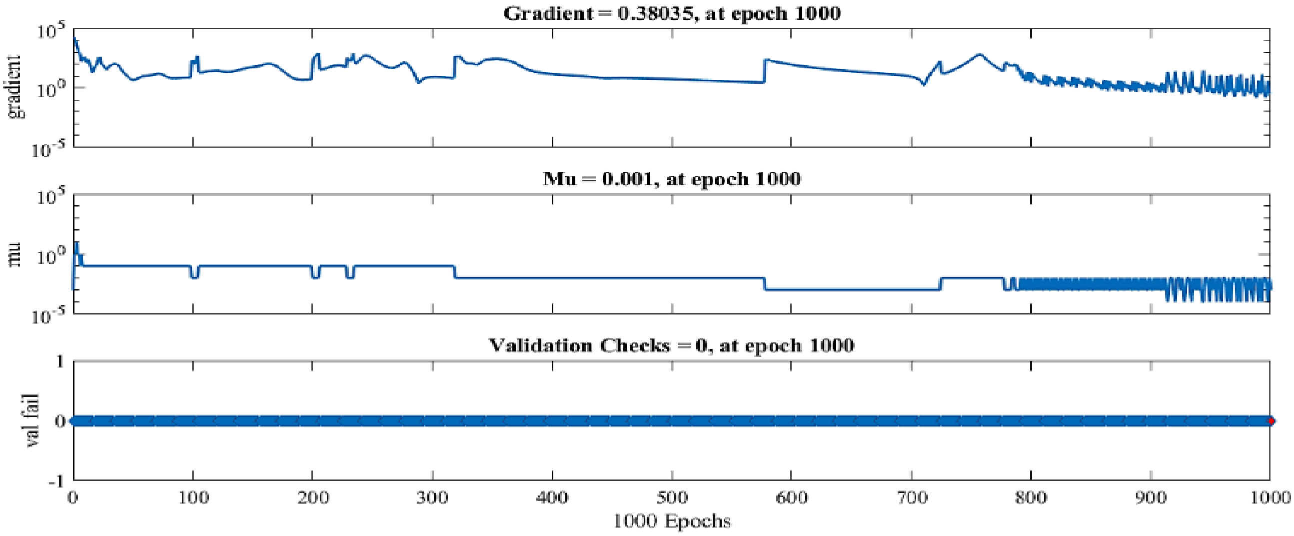


Figure 6-24. Data training evaluation and validation using GA-HNN

Figures 6-24 and 6-25 present the data training evaluation and validation, time series response of training the created net of RES penetration effects for both NREL 118 and ERES. It can be seen that the demand and supply are affected by the intermittent and variable renewables.

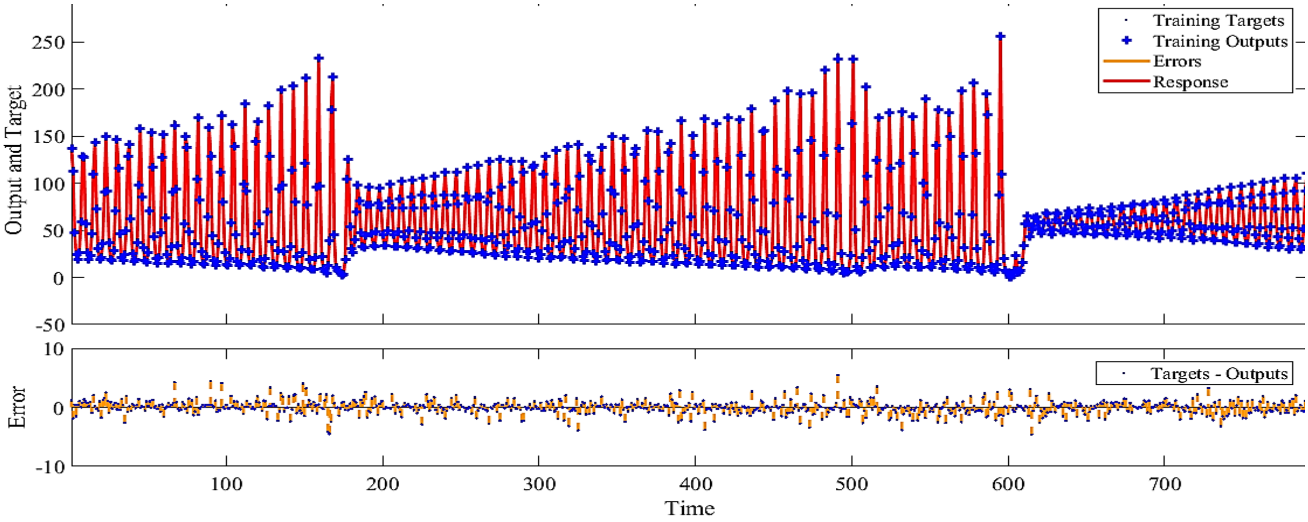


Figure 6-25. Time series response of training the created GA-HNN

To practically interpret the results, unit commitment input, forecasted data evaluated by predictive control of GA-HNN, the number of recursive blackouts, and demand profile are integrated within the proposed SCED solution. From weight positions plotted and their time series response of their training in Figure 6-25, the attractor pattern on the final state, penalty function weight, and adaptive calculation of weighting factors can be obtained

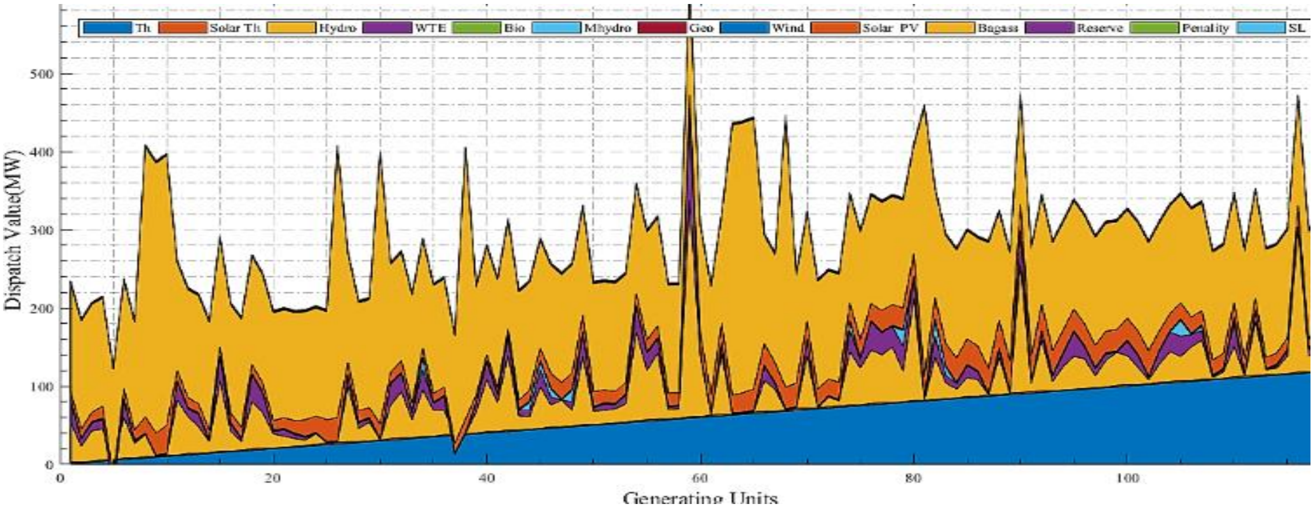


Figure 6-26. Dispatch value of generating units by the technology of the NREL 118 bus system

The modified IEEE- 118 test system also known as, NREL 118 test system, provides a researcher with the privilege of choosing and editing renewable penetrated zones based on their resemblance to a particular project. Accordingly, Figure 2-27 depicts ERS adopted from NREL 118 test system zones 2&3.

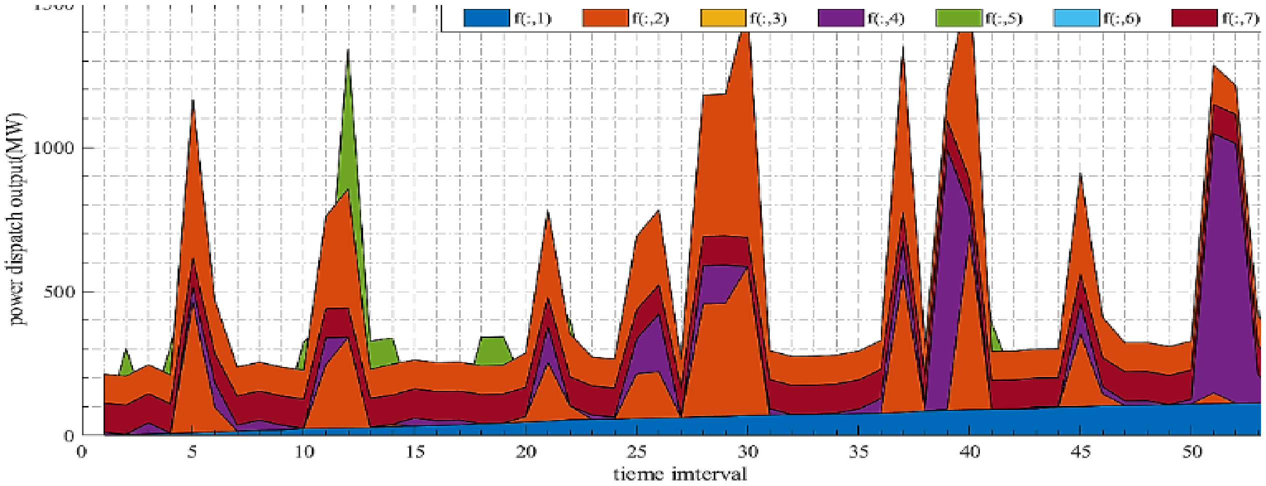


Figure 6-27 Dispatch value of NREL 118 bus system

Figure 6-28 thus helps to grasp the effect of weekend demand profiles on SCED of ERES. Figure 6-29 presents dispatch contributions from Ethiopian existing power plants participated in alleviating the recursive blackouts. In Ethiopia, the weather does not significantly vary throughout the year. Apart from solar PV generation, therefore, demand seasonality on the grid is minimal. Here, the residential demand is characterized by lighting, cooking, and heating and since the peak is in the evening, their contribution to the system peak is significant.

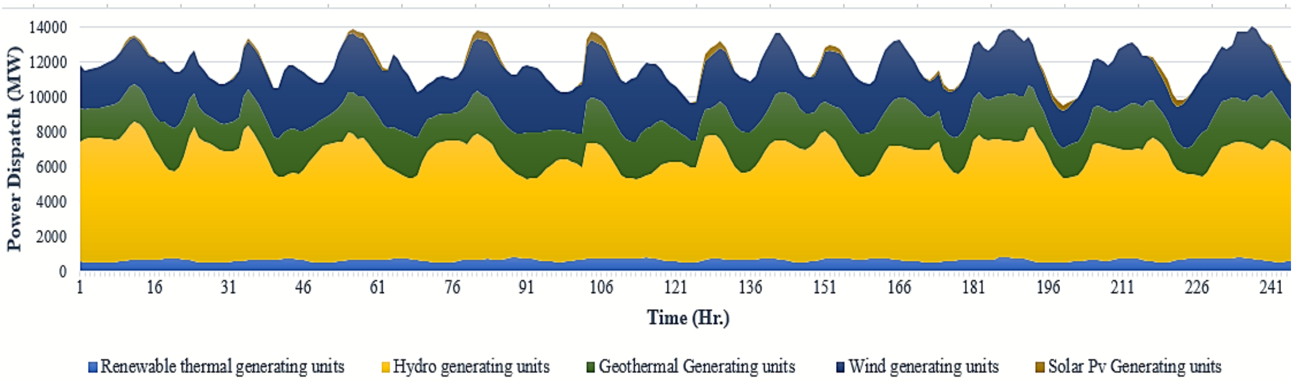


Figure 6-28. Ethiopian Renewable Energy Systems dispatch

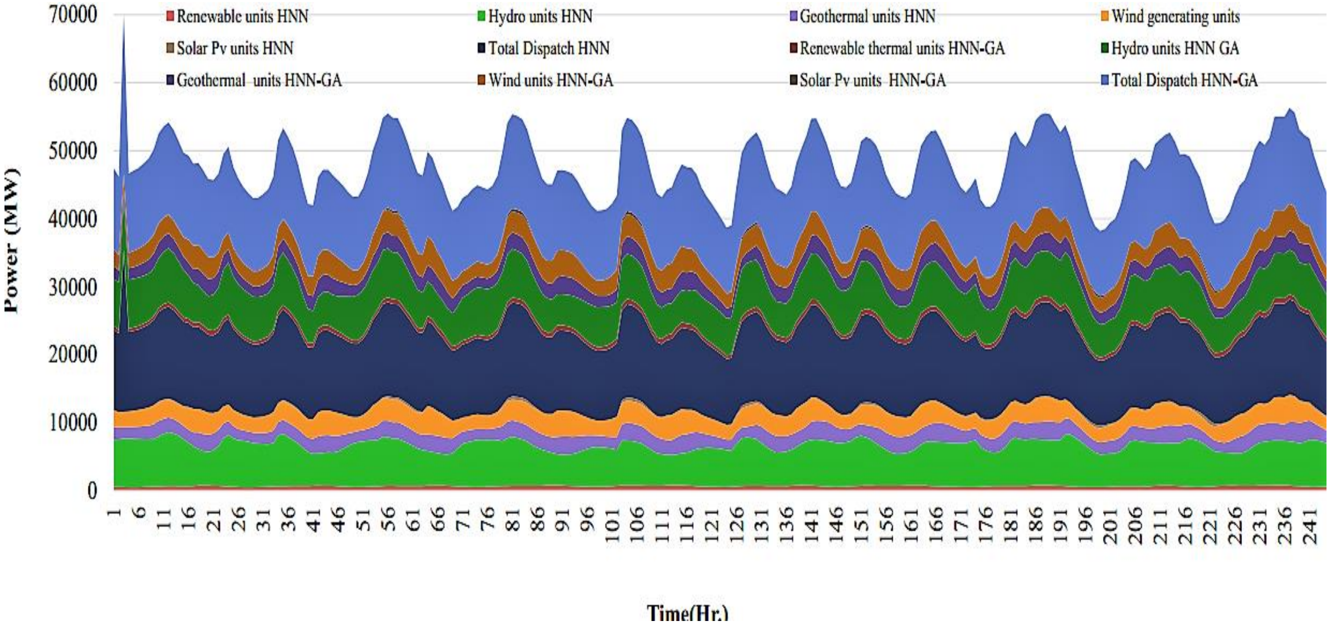


Figure 6-29. Comparison Ethiopian Renewable Energy Systems dispatch results using two different solution methods, HNN and GA-HNN

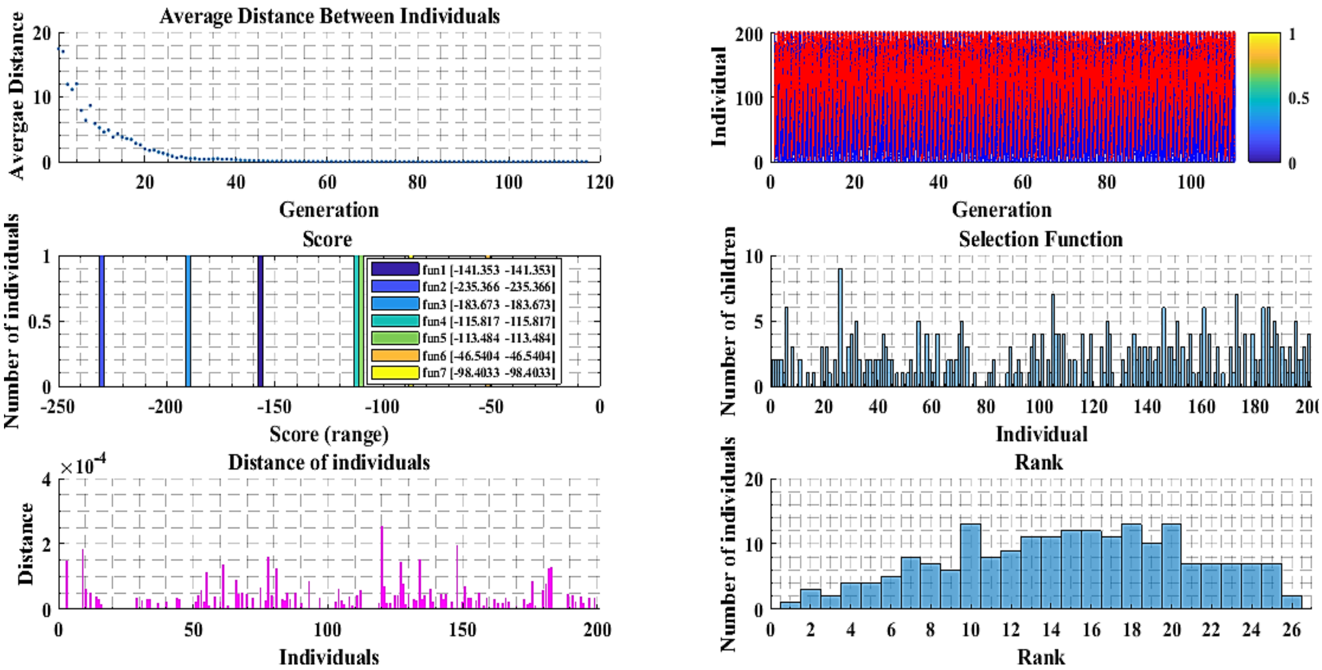


Figure 6-30. Results showing HNN enhanced GA features and properties

TABLE 6-6. TWENTY-FOUR HOURS DISPATCH RESULTS OF ETHIOPIAN RENEWABLE ENERGY SYSTEMS

Time (Hr.)	Renewable thermal Un	Hydro Units	Geothermal Units	Wind Turbines	Solar PV units	Total Dispatch
1	546.5296	6908.06298	1904.444801	2486.384086	0	11849.04155
2	500.538208	7045.33766	1726.281344	2274.63274	0	11549.12606
3	480.946792	7175.19474	1694.941121	2256.4587	0	23394.16761
4	474.983941	7201.020161	1680.003245	2302.019176	0	11664.1314
5	473.247513	7164.612328	1726.221344	2399.06995	0	11769.15114
8	482.488935	7106.253761	1817.709385	2460.56778	0	11865.71086
7	505.000219	7040.330195	1936.525024	2554.02187	0	12034.88594
8	522.417476	7004.180391	2033.011569	2661.012358	0.0197079	12219.79114
9	554.883166	7022.053958	2164.651049	2739.72059	62.82363031	12543.93396
10	596.019562	7399.12731	2241.881214	2770.462473	122.9885806	13130.47914
11	623.0324	7722.260857	2232.45963	2729.88846	90.85627255	13397.92534
12	638.19096	7958.937268	2169.403675	2653.633699	120.6441083	13540.30971
13	641.028101	7772.054425	2096.936135	2619.199955	131.1142355	13260.92285
14	637.02389	7446.678735	2017.329658	2642.56571	116.26645	12859.55294
15	631.0012393	6957.115201	1941.277649	2808.585546	93.34304056	12431.65383
16	622.471685	6426.484527	1885.434299	3309.104608	69.32081069	12312.81593
17	646.632381	5898.015282	2003.061781	3448.06936	21.67234823	12017.45115
18	721.010367	5408.451748	2415.352046	3496.030646	0	12041.07891
19	736.02783	5064.784631	2514.969026	3442.047792	0	11757.05716
20	724.571605	4977.246781	2483.07696	3268.521981	0	11453.41733
21	712.724472	5254.990331	2433.550705	3021.336892	0	11424.6024
22	682.378378	5901.257424	2344.062663	2727.420293	0	11654.52416
23	623.570255	7089.233496	2164.651049	2488.843639	0	12368.02728
24	570.083154	7684.43586	1967.41709	2420.205928	0	12642.14203
P loss (MW)						35.00023
Cost ($/MW)	49008.67608	250772.5612	101272.2803	118214.0358	1347.204925	520614.7584

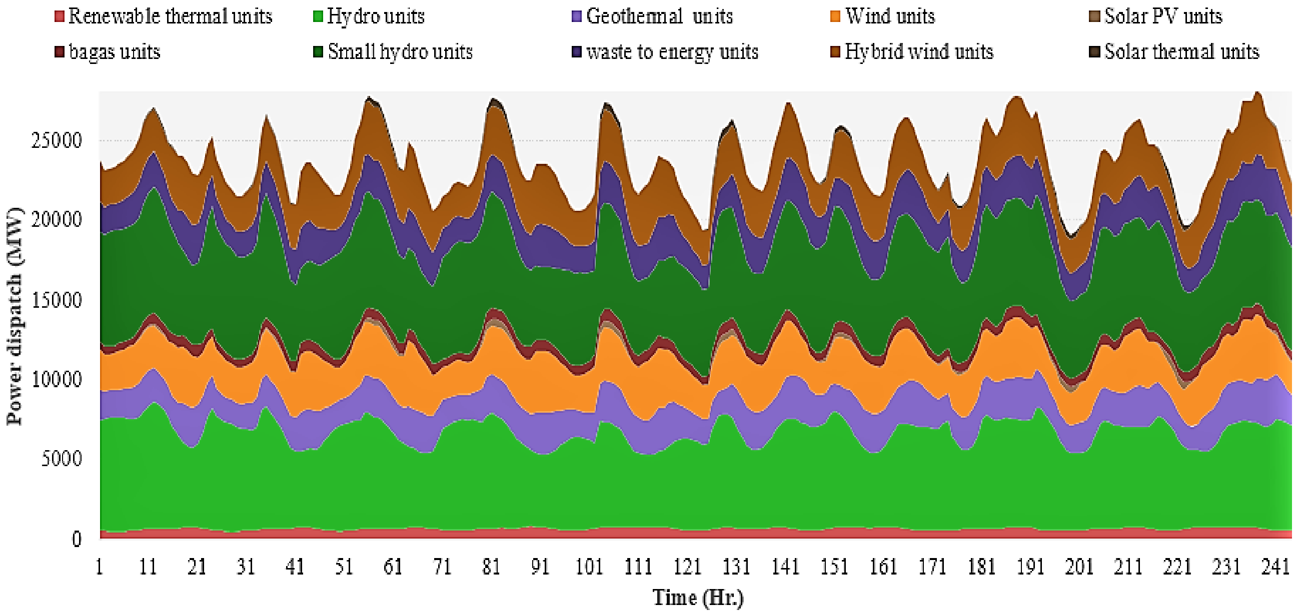
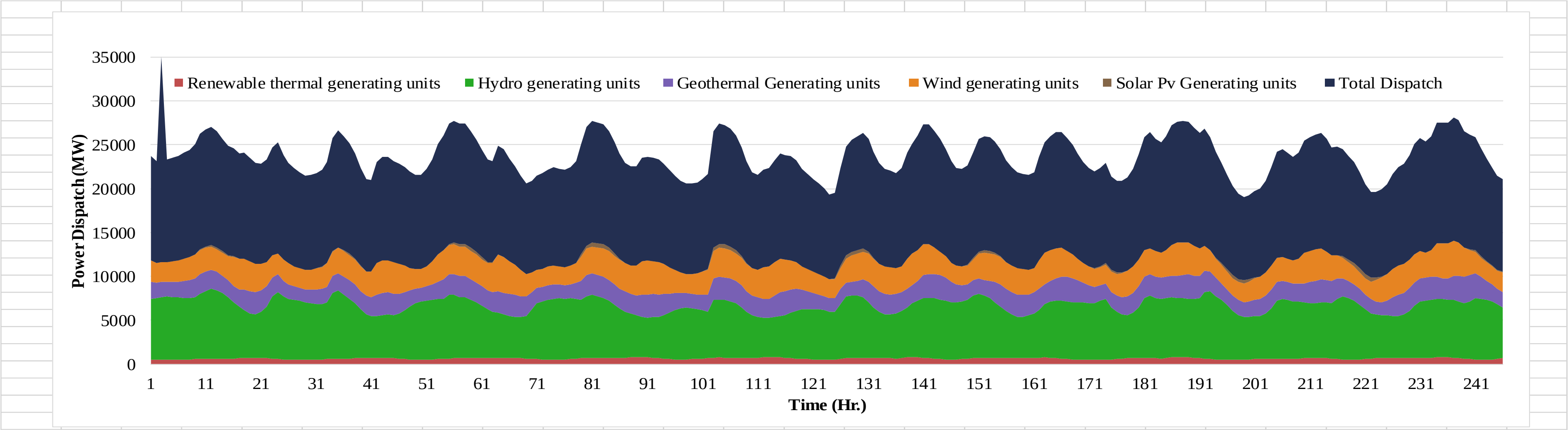


Figure 6-31**.** Weekly dispatch Ethiopian Renewable Energy System

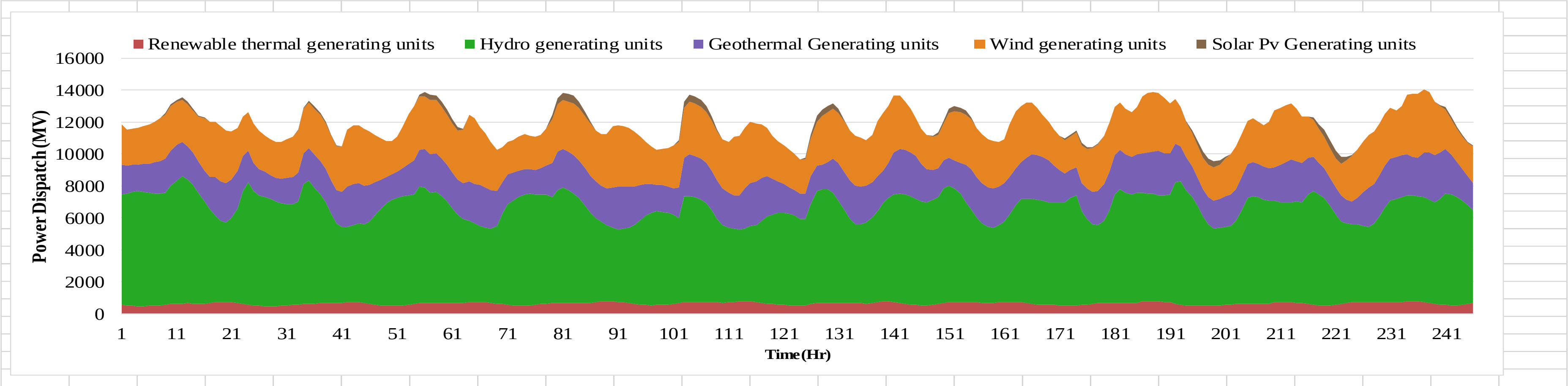
Figure 6-31 depicts energy share and dispatch of each Ethiopian generating unit committed so far to supply 10.023GW of power. A comparison between the proposed solution methods of economic dispatch for all case studies of renewable generation are presented in Tables 6-7 and 6-8. The importance and prospect of employing each solution method can be seen from the simulation results presented from figure 6-32 to figure 6-35.

TABLE 6-7. MULTI-VARIABLE MULTI-OBJECTIVE SIMULATION DISPATCH COMPARISONS OF HNN, EPGA, AND GA-HNN

Time(Hrs)	HNN Solution(MW)	EPGA Solution(MW)	GA-HNN Solution(MW)
1	11847.04	11847.04155	11850.04155
2	11547.13	11547.12606	11550.12606
3	23394.17	23394.16761	23395.16761
4	11662.13	11662.1314	11665.1314
5	11768.15	11768.15114	11770.15114
8	11866.71	11866.71086	11865.71086
7	12034.89	12034.88594	12035.88594
8	12219.79	12219.79114	12220.79114
9	12543.93	12543.93396	12545.93396
10	13130.48	13130.47914	13130.47914
11	13397.93	13397.92534	13400.92534
12	13540.31	13540.30971	13540.30971
13	13260.92	13260.92285	13260.92285
14	12859.55	12859.55294	12860.55294
15	12431.65	12431.65383	12435.65383
16	12312.82	12312.81593	12315.81593
17	12017.45	12017.45115	12017.45115
18	12041.08	12041.07891	12045.07891
19	11757.06	11757.05716	11760.05716
20	11453.42	11453.41733	11455.41733
21	11424.6	11424.6024	11425.6024
22	11654.52	11654.52416	11655.52416
23	12368.03	12368.02728	12370.02728
24	12642.14	12642.14203	12645.14203
Pm(MW)	3.22315E-05	3.16214E-05	2.85323E-06
P loss	36.78	36.23	35.23
Cost ($/)	520,614.85	520,001.24	519,971.00
Runtime (sec)	0.6875	0.2692	0.12812



(a)



(b)

Figure 6-32. Ten days EPGA based dispatch that includes weekends for ERES (a). With emphasis on hydropower dispatch (b). With significant dispatch on the total dispatch

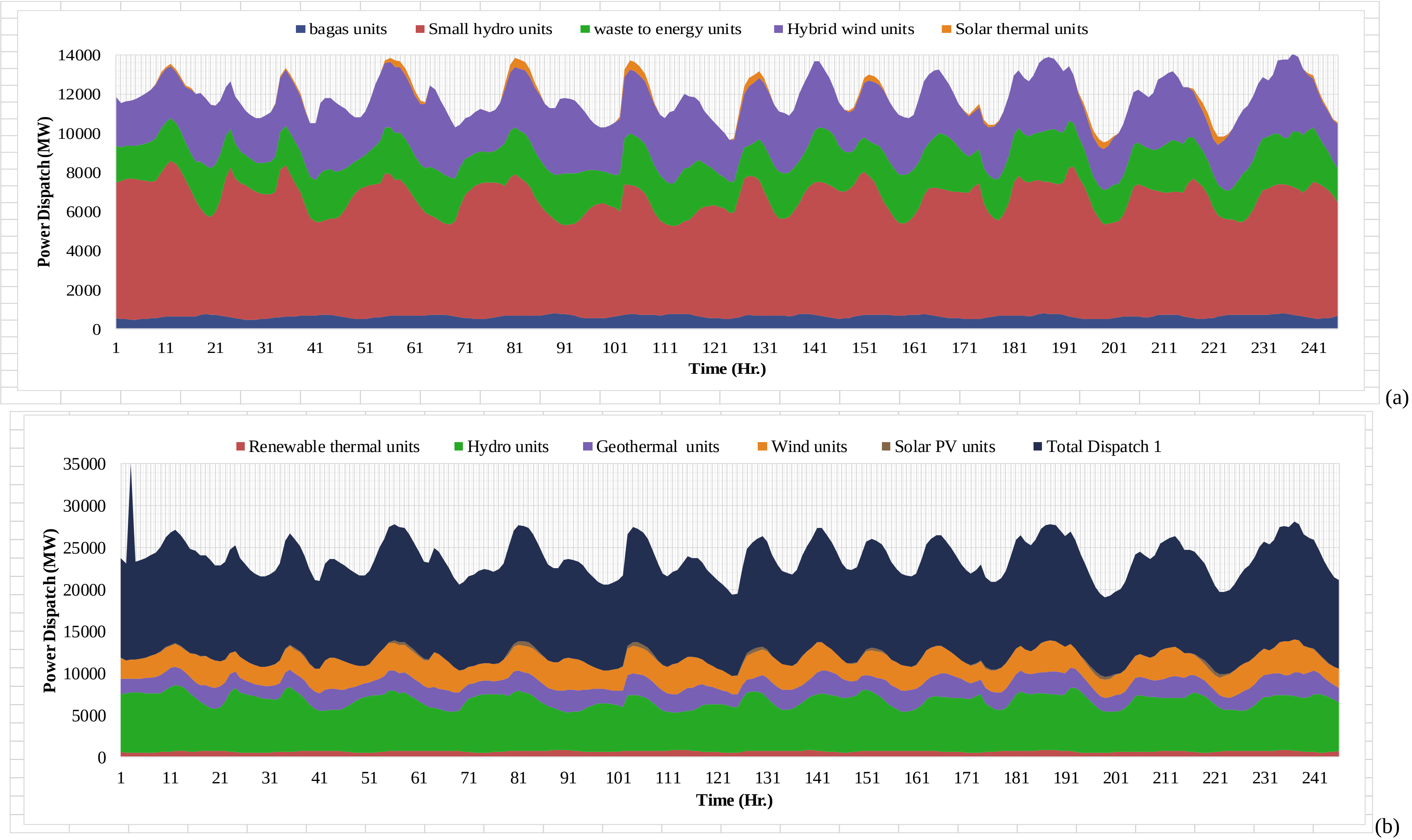
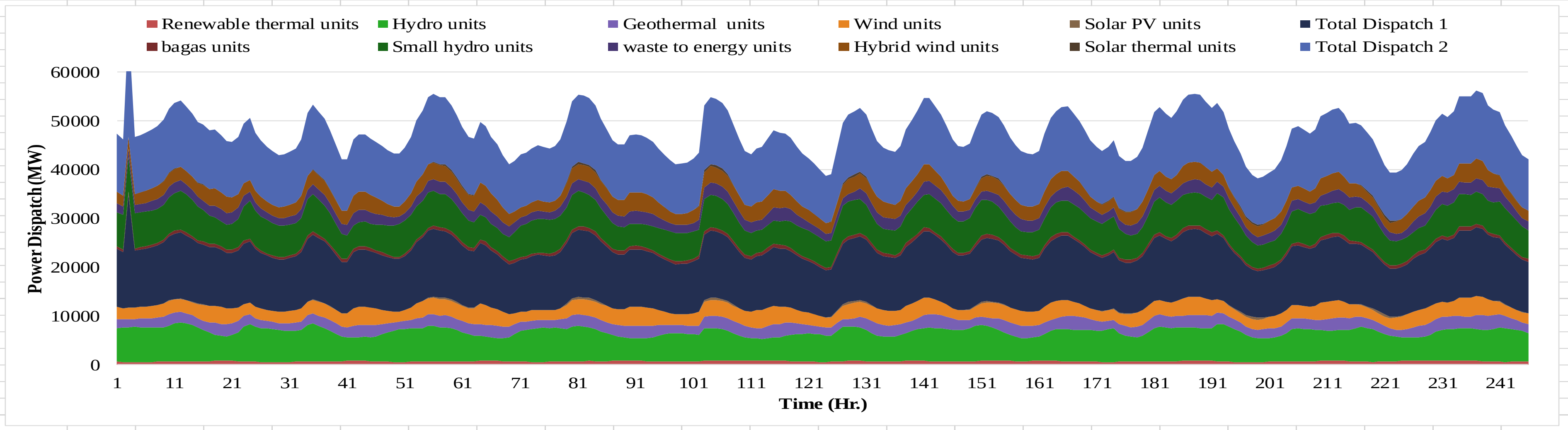
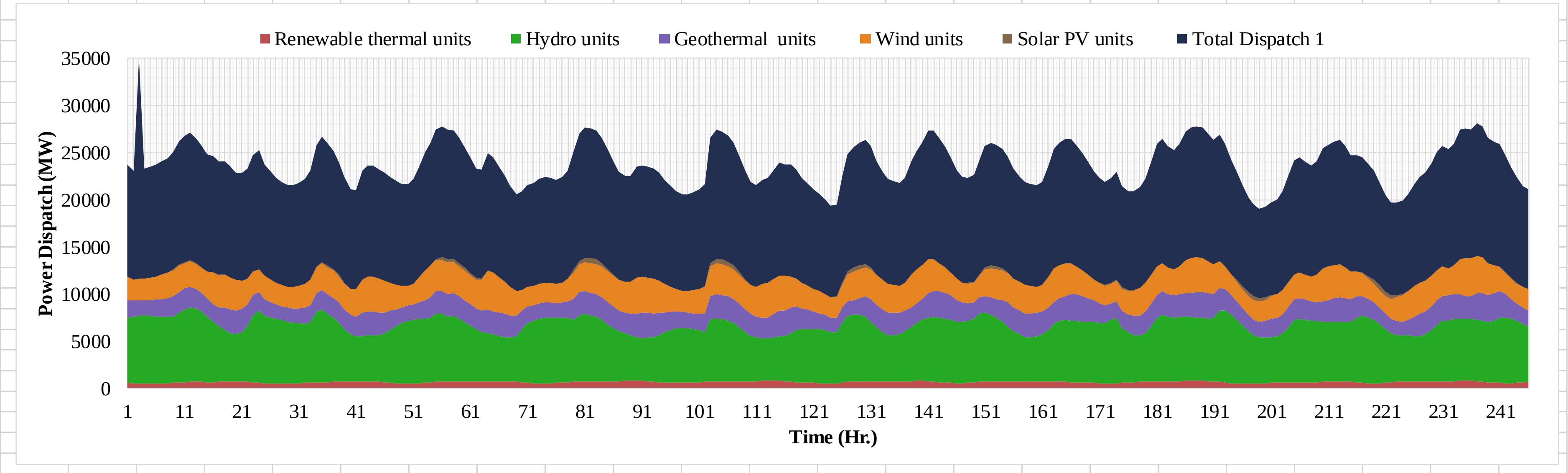


Figure 6-33. Ten days HNN based dispatch that includes weekends for ERES (a). With emphasis on hydropower dispatch (b). With significant dispatch on the total dispatch

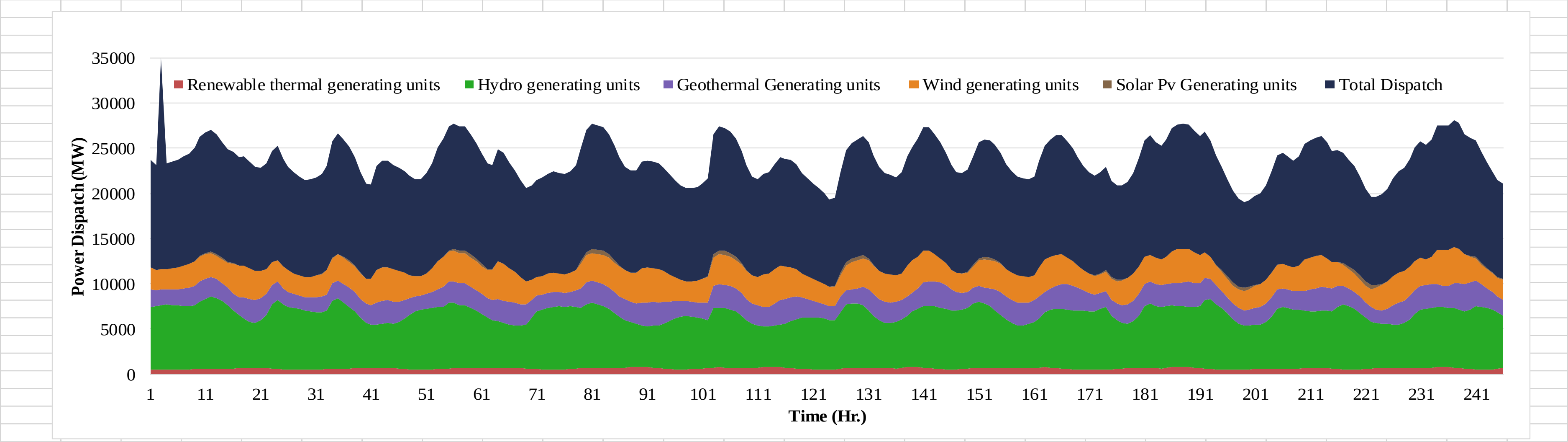


(a)

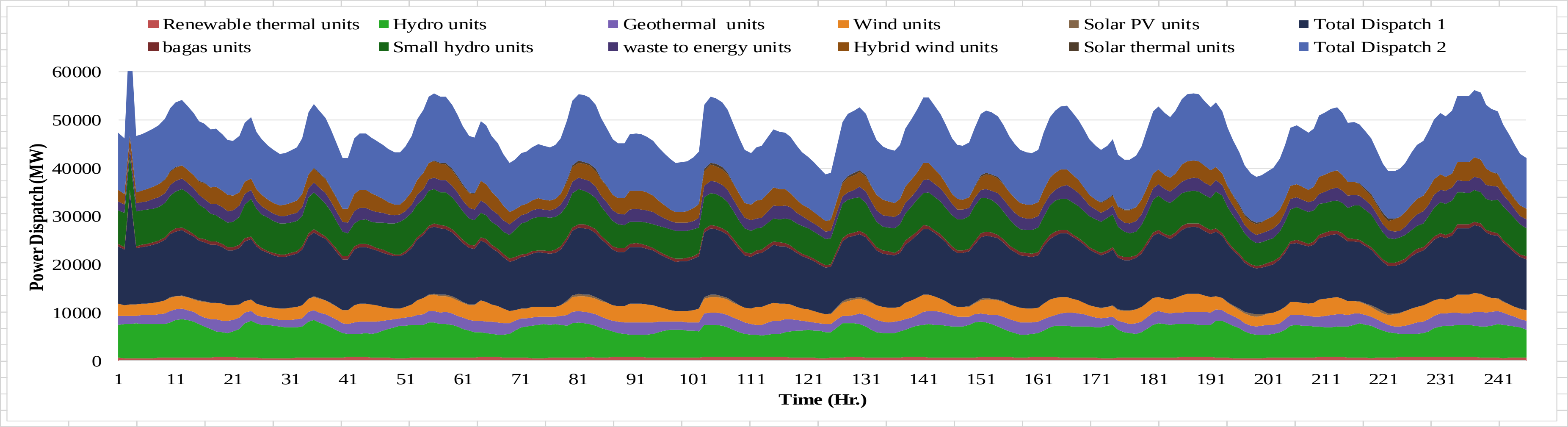


(b)

Figure 6-34. Ten days dispatch that includes weekends for ERES (a). With emphasis on HNN and EGPA comparison (b). With significant emphasis on the total dispatch of generation technology



(a)



(b)

Figure 6-35. Ten days optimal dispatch that includes weekends for ERES (a). With emphasis on system security (b). With significant emphasis on the total cost

TABLE 6-8. COMPUTATIONAL DISPATCH COMPARISON OF THE UTILIZED SOLUTION METHODS FOR SOLVING SCED OF IRES

Time	HNN Solution	EPGA Solution	HNN-GA Solution
1	↓ 11847.04	↓ 11847.04155	11850.04155
2	↓ 11547.13	↓ 11547.12606	11550.12606
3	↑ 23394.17	↑ 23394.16761	23395.16761
4	↓ 11662.13	↓ 11662.1314	11665.1314
5	↓ 11768.15	↓ 11768.15114	11770.15114
8	↓ 11866.71	↓ 11866.71086	11865.71086
7	↓ 12034.89	↓ 12034.88594	12035.88594
8	↓ 12219.79	↓ 12219.79114	12220.79114
9	↓ 12543.93	↓ 12543.93396	12545.93396
10	↓ 13130.48	↓ 13130.47914	13130.47914
11	↓ 13397.93	↓ 13397.92534	13400.92534
12	↓ 13540.31	↓ 13540.30971	13540.30971
13	↓ 13260.92	↓ 13260.92285	13260.92285
14	↓ 12859.55	↓ 12859.55294	12860.55294
15	↓ 12431.65	↓ 12431.65383	12435.65383
16	↓ 12312.82	↓ 12312.81593	12315.81593
17	↓ 12017.45	↓ 12017.45115	12017.45115
18	↓ 12041.08	↓ 12041.07891	12045.07891
19	↓ 11757.06	↓ 11757.05716	11760.05716
20	↓ 11453.42	↓ 11453.41733	11455.41733
21	↓ 11424.6	↓ 11424.6024	11425.6024
22	↓ 11654.52	↓ 11654.52416	11655.52416
23	↓ 12368.03	↓ 12368.02728	12370.02728
24	↓ 12642.14	↓ 12642.14203	12645.14203
Pm(MW)	3.22315E-05	3.16214E-05	2.85323E-06
P loss (MW)	36.78	36.23	35.23
Cost($/MW)	520,614.85	520,001.24	519,971.00
Run time (sec)	0.6875	0.2692	0.12812

6.2. Discussions

SCED can be solved by different solution methods based on the assumed type of data parameters. For a fixed generation and a fixed demand, simple analytical methods can be utilized. These include lambda oration, gradient method, newton Raphson method and linear programming methods. Even though having a fixed demand is ideal, fixed generation/supply can be provided from the conventional and phasing out thermal power plants. As thermal power plants do not comply with the global Climate Resilient Green Economy (CRGE), it is difficult to conclude the existence of fixed generation in today's power systems. Recent and modern power systems are either hybrid energy systems or integrated renewable energy systems that supply intermittent and variable generation. Demand profiles of these power systems in connection with different sectors and application are also variable.

For this reason, a power system operator and planner needs to consider these challenges. One daily operation task a power system operator can do to address the challenges discussed in the motivation and problem statement sections is SCED. SCED coins both the power mismatch and intermittency challenges. When SCED is applied for integrated renewable energy systems, its main objective is to determine optimal generation level, not significantly reducing fuel cost. It emphasizes on allocating generation level so that the variable demand and the variable generation can be concurrently balanced. The term 'Economic' is an adjective implying that the dispatch, ordering a generating unit to generate more or less power, should be done economically. For such kind of practical challenges, the conventional and analytical methods lack computational capability of solving SCED for IRES.

Solution methods used to solve SCED of IRES in this dissertation are thus, Multi-Objective Multi-Variable optimization (MVMO), Efficient and Parallel Genetic Algorithm (EPGA), Hopfield Neural Network (HNN) and hybrid Genetic Algorithm-Hopfield Neural Network (GA-HNN) approaches. Modified New England 39 bus system and modified IEEE 118 bus system (NREL-118 bus system) were used as test systems to check the performance and robustness of the formulated mathematical frameworks. Then a physical power system, the Ethiopian Renewable Energy Systems (ERES) was used to address supply-demand imbalance caused recursive blackouts in the power system.

According to the results obtained, hybrid GA-HNN helps to determine SCED global optimum solution of integrated, intermittent renewable energy systems. The obtained results include saving 0.519 million $/MW within 24 hours of operation at power loss of only 35.23 MW. This makes the proposed approach a strong financial solution in renewable energy markets. Utilizing hybrid GA-HNN resulted in the reduction of power mismatch by 23%. This mismatch enables power system operator deal with the unserved customers and unserved energy produce. Moreover, number of recursive blackouts were reduced by 12.36 % and execution time of the solution method by 56.89 %. In Ethiopia, the weather does not significantly vary throughout the year. Apart from solar PV generation, therefore, demand seasonality on the grid is minimal. Here, the residential demand is characterized by lighting, cooking, and heating and since the peak is at the evening, their contribution to the system peak is significant.

The composition of the load is probably different as the state cities’ commercial and public services of large infrastructure, industries, schools and hospitals working mainly between 8:00 Am and 6:00 Pm. Additionally, the country’s suburbs can largely consist of small shops, hotels, bars, cafés and restaurants that stay open throughout the evening. SCED is important for scheduling when/which generator to dispatch, determining how much reserve is need for spinning, standby, ramping and contingency. It is in such situations, the significance of SCED for renewable generation is pivotal. The results addressed most of the challenges depicted in the motivating problem that gave rise to this study.

Chapter 7. Concluding Remarks

7.1. Summary

A sudden change in a variable renewable source can cause a large surplus or lack of power output that subsequently affects security or even adequacy in power system networks with limited flexibility. Moreover, blackouts can impose discouraging and considerable damage to service centers, production plants and home appliances. This damage threatens the socio-economic endeavors of the community. Most blackouts are caused by challenges related to intermittency, variability and non-dispatch ability of IRES.

With increasing emphasis on improving efficiency and utilizing more renewable energy to mitigate climate change effects, the power industry is confronted with such generation-demand mismatch challenges. The main problem of integrated energy systems in countries like Ethiopia is that the electric power service they provide is insecure, non-reliable and faces many hindrances with regard to providing continuous service. This aspect requires an accurate method of balancing between generation and demand taking into account generation limits, transmission constraints, contingencies and uncertainties i.e. security constrained economic dispatch (SCED).

This Ph.D. research/ dissertation presents optimization of security-constrained economic dispatch for IRES. It encompasses the determination of optimal generation cost of different IRES using a hybrid Genetic Algorithm-Hopfield Neural Network (GA-HNN) to determine a global maximum solution of renewable energy sources. The outcome of this research can enable RES fed power systems with limited flexibility to deal with the variability and intermittency of both generation and demand as the computational method can adapt and learn varying characteristics of renewable sources. Proposing methods to handle credible contingencies and selecting ways to take post contingency rescheduling actions are also part of this Dissertation. Power systems with limited flexibility, renewable micro grids, islanded smart grids and grids with fluctuating demand and generation patterns can take advantage of this research.

The potential beneficiaries of the outcome of this research include: Short-term power system operation planners, energy management experts, electricity and energy regulators, power system economists, transmission system operators (TSOs), profit oriented independent power producers, renewables to grid integrators and economic power dispatch advocators. After conducting this research, the researcher has addressed the following research gaps and their corresponding research objectives:

- A comprehensive survey on recent trends and state-of-the-art of SCED applied for renewable energy sources was not reported. The researcher conducted a literature review showing the future research avenues of SCED for IRES as a separate article or conference paper.
- Mathematical SCED objective function for a combination of more than three types of renewable energy conversion technologies was never formulated before. This research provides objective function formulation subject to considerable constraints comprising biomass, wind, solar, geothermal, hydro, and waste to energy conversion technologies.
- There are no concrete shreds of evidences that claim SCED of IRES with contingencies and uncertainty factors. The research provided contingency handling mechanisms in connection with credible contingency constraint formulation.
- Hybrid HNN-GA algorithm was not applied for solving SCED before and there is no clear indication on how the Ethiopian power system network is economically dispatched. This research proposed and applied hybrid GA-HNN to solve SCED of IRES using the Ethiopian power system, IEEE 118 Bus system and New England 39 bus system as case studies.

7.2. Contributions

This dissertation encompasses:

1. Review on recent research avenues and state of the art of SCED applied for renewable energy sources and hybrid systems. Recent Trends on Security Constrained Economic Dispatch: A Bibliographic Review a survey of articles, books and reports, which articulate the recent trends and aspects of Security Constrained Economic Dispatch (SCED). The period under consideration is 2008 through 2018. This is done to provide an up-to date review of the recent major advancements in SCED, the state-of the-art since 2008, identify further challenging developments needed in smarter grids, and indicate ways to address these challenges. This study consists of three areas of interest, which are very important and relevant for articulating the recent trends of SCED.

2. A Review on Security Constrained Economic Dispatch of Integrated Renewable Energy Systems. This helps identify further challenges needed in adopting smarter grids, and indicate ways to address these challenges. The study was conducted in three areas of interest that are relevant for articulating the recent trends of SCED.
3. Security Constrained Economic Dispatch (SCED) of renewable energy systems (RES). Reformulation of SCED for RES comprising biomass, large and micro-hydro plants, solar PV, solar thermal, waste to energy plant, wind farm and geothermal has been carried out. This enables RES prime-moved power systems to provide secure and reliable service.
4. Security Constrained Economic Dispatch of Ethiopian Renewable Energy Systems: Prospects and challenges. This contribution presents the prospects and challenges of Security Constrained Economic Dispatch (SCED) for Ethiopian Renewable Energy Systems (ERES), which is a non-existent practice in the Ethiopian generation plan. This is done to provide state-of-the-art advancements and the importance of SCED for the Ethiopian power network.
5. Security Constrained Economic Dispatch of Ethiopian Renewable Energy Systems using Genetic Algorithms. Security Constrained Economic Dispatch (SCED) of Ethiopian Renewable Energy Systems (ERES) using Efficient Parallel Genetic Algorithm (EPGA). The mathematical framework of SCED for ERES comprising of biomass, large and micro-hydro plants, solar PV, solar thermal, waste to energy plant, wind farm and geothermal with their constraint formulations is presented.

   A general overview of ERES, altogether with demand forecast, power mismatch and 5-10 day dispatch is also presented. This enables ERES to enhance the under construction automatic dispatch center to provide secure and reliable service. The non-existence of such dispatch center in Ethiopia is one of the main reasons for supply-demand imbalance and recursive blackouts. This contribution argues that computationally intelligent economic dispatch limits and decreases the occurrences of blackouts and interruptions in the Ethiopian power system.
6. Hopfield Neural Network-based Security Constrained Economic Dispatch of Renewable Energy Systems. Modified IEEE 118 bus system and Ethiopian renewable energy systems were used as case studies. Modelling and simulation were conducted on MATLAB. According to the results obtained, it can be deduced that employing HNN based SCED is a promising step in connection to developments needed in the adoption and realization of smarter grids as

it reduces execution time, production cost and the number of blackouts while increasing the security level of a power system of RES.

7. Optimal Security Constrained Economic Dispatch of Renewable Energy Systems using hybrid Hopfield Neural Network-Genetic Algorithm approach. Modified IEEE 118 bus system (NREL-118 test system) and Ethiopian Renewable Energy Systems (ERES) were used as case studies. Modelling and simulation were conducted on MATLAB, MATLAB/MATPOER simulation platforms.

   According to the simulation results obtained, it can be deduced that economic dispatch of RES using hybrid GA-HNN is a promising step in connection to developments needed in the adoption and realization of smarter grids as it is an excellent solution method of anticipating intermittent fluctuations and predictive control. Optimal generation dispatch of modified IEEE 118 bus system and Ethiopian energy system using hybrid Genetic Algorithm-Hopfield Neural Network (GA-HNN). This approach helps to determine SCED global optimum solution.

7.3. Future work

Relevant literature on the background of renewable energy systems and integrated renewable energy systems in relation to State of the art operation principle and the basic science behind the most common renewable energy sources with their maps of potential reserve globally, regionally and nationally should be revisited. Arguments on why we need renewable energy systems in compliance to Climate Resilient Green Economy (CRGE) strategy, what their challenges are in the electricity markets with respect to correction and prevention costs, and how these challenges can lead to recursive power surges, service interruptions, and blackouts need both intensive and extensive research. Figuring out a way of solving this multi-objective optimization problem that considers variable loads & intermittent generation is a challenge that requires substantial attention during the integration of renewables.

For future work, hybrid computational intelligence based optimization of SCED for IRES with predictive control and post contingency corrective actions is proposed. This could alleviate the challenges related to the intermittency and unpredictability of renewable energy sources. Besides using physical power systems, applying computationally intelligent and self-adaptive optimization tools of SCED for renewable micro grids, smart grids, and hybrid energy systems is also suggested. As long as the power system is renewables fueled, advanced SCED mathematical formulation can result in a promising optimal solution.

Economic dispatch of IRES using HNN is a promising step in connection to developments needed in the adoption and realization of smarter grids as it is an excellent solution method of anticipating intermittent, fluctuating and variable renewable energy systems. HNN can also provide accurate forecast and predictive control of contingencies. It has also a feature for involved multi-objective functions to share feedback and train from them. HNN is an excellent solution method of variability. However, premature convergence and the inability to provide global optimum solutions still is its drawback that needs intensive research and improvements.

Hybrid solutions such as hybrid HNN-Genetic Algorithm methods can overcome these drawbacks. Enhanced genetic algorithms are the best solution methods of obtaining a global optimum solution of multi-objective SCED given their efficient, and parallel computing features. Hybrid options can also be taken to increase the convergence problem of genetic algorithms. Hybrid HNN-Genetic Algorithm methods can be utilized for other computational challenges in power systems such as unit commitment, contingency analysis, and power flow analysis.

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Appendix A

MATALB code for Objective functions

```
% the follwoing objective function is developed from equations (6)-(25)
%of the decument according the concepts and mathematical formulations of
%equations (1)-(5)
function y=sced_multiobjective(x)
         y=zeros(6,1)
% compute the first objective function
% the objective function about hydropower ecnomic dispatch
       for i=47   % number of considered hydropower generating units
           y(1)= y(1)+Ch*x(i)   % Ch is hydropower genration cost
     end;
% compute the second objective function
% the objective function about wind power ecnomic dispatch
       for i=306  % number of considered wind turbines
           y(2)= y(2)+ Cw*x(i) +Cp+Cr   % Cw, Cp and Cr are wind geneation cost,
% wind generation penalty cost and wind generation reserve cost respectiveky
       end;
% compute the the third objective functin
% the objective function about solar PV power economic dispatch
      for i=17   % number of considered PV generating plants
          y(3)= y(3)+ Cs*x(i) +Cp+Cr  % Cs, Cp and Cr are Solar PV geneation cost,
%Solar PV generation penalty cost and Solar PVgeneration reserve cost respectiveky
       end;
% compute the fourth objective function
% the objective functin about renewbale thermal power economic dispatch
     Crth= alpha*(ai +bi+ci)
     for i=62
```

```
        y(4)= y(4)+Crth*x(i)    % Crth is renewable thermal generation cost
    end;
% compute the fifth objective function
% the objective function about security index
    NL= 102 % number of transmission lines
   for i= 102
       y(5)= y(5)+ (x(i)/x(i.)^2*56
      end;
```

Constraint Functions

```
      function [c,ceq] = sced_confuneq(x)
% Nonlinear inequality constraints
c = -x(1)*x(2) - 10;
% Nonlinear equality constraints
ceq = x(1)^2 + x(2) - 1;
end

A = [];
b = [];
Aeq = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];
beq = PD; %%Total
lb = [14 14 14 14 60 20 20 20 100 61.3 61.3 61.3 38.4 60 20 40 40 11 16 5  20 25 10
32 32 32 32.3 354 354 354 354 354 354 354 354 354 354 106. 106.7 16 38 38 38 38 100
40 40 2.5 2.5 111 111 111 111 74.25 74.25 74.25 74.25 70 34 34 82 ];  %%Lower
boundary
ub = [51 120 153 120 16 16 16 16 120 30 30 20 100 61.3 61.3 61.3 43 138 60 60 60
11.4 30 7.3 30 25 31 33.3 33.3 33.3 34 400 400 400 400 400 400 400 400 400 400 400
400 400 400 375 375 107 107 107 107 187 187 187 187 187 187 187 187 187 187 26 38
38 38 38 100 60 60 2.5 2.5 115 115 115 115 75 75 75 75 120 36.8 36.8 133 ];
fitnessFunction=@x[y1, y2, y3, y4, y5] % f1(x), f2(x), f3(x), f4(x), f5(x)
nvars=5;
lb = [14 14 14 14 60 20 20 20 100 61.3 61.3 61.3 38.4 60 20 40 40 11 16 5  20 25 10
32 32 32 32.3 354 354 354 354 354 354 354 354 354 354 106.7 106.7 16 38 38 38 38
100 40 40 2.5 2.5 111 111 111 111 74.25 74.25 74.25 74.25 70 34 34 82 ];  %%Lower
boundary
ub = [51 120 153 120 16 16 16 16 120 30 30 20 100 61.3 61.3 61.3 43 138 60 60 60
11.4 30 7.3 30 25 31 33.3 33.3 33.3 34 400 400
400 400 400 400 400 400 400 400 400 400 400 400 375 375 107 107 107 107 187 187 187
187 187 187 187 187 187 187 26 38 38 38 38 100 60 60 2.5 2.5 115 115 115 115 75 75
75 75 120 36.8 36.8 133 ];
rng default;
x=gamultiobj(fitnessFunction, nvars, [], [], [], [], lb, ub)
% otmizing the objective functions unsing multobjective genetic algorithm
Fitness function =@sced_multiobjective(x)
nvars=5;
```

```
lb = [14 14 14 14 60 20 20 20 100 61.3 61.3 61.3 38.4 60 20 40 40 11 16 5  20 25 10
32 32 32 32.3 354 354 354 354 354 354 354 354 354 354 106.7 106.7 16 38 38 38 38
100 40 40 2.5 2.5 111 111 111 111 74.25 74.25 74.25 74.25 70 34 34 82 ];  %%Lower
boundary
ub = [51 120 153 120 16 16 16 16 120 30 30 20 100 61.3 61.3 61.3 43 138 60 60 60
11.4 30 7.3 30 25 31 33.3 33.3 33.3 34 400 400 400 400 400 400 400 400 400 400 400
400 400 400 375 375 107 107 107 107 187 187 187 187 187 187 187 187 187 187 26 38
38 38 38 100 60 60 2.5 2.5 115 115 115 115 75 75 75 75 120 36.8 36.8 133 ];
ConstarintFunction=@sced_confuneq(x);
options=optimoptions(@ga, 'mutationFcn', @mutationadaptfeasible);
[x,fval]=gamultiobj(FitnessFunction, nvars, [], [], [], [], lb,
ub...constarint Functions,Options)
```

MATLAB code for inserting data

```
% load the ethiopian renewable energy systems data parametres

% only renewables incuding renewable thermal power plants adopted from

% conventional thermal power plants

function [d]=data_ERES

%  n    a     b     c   min  max       plant

d= [1    -   15.5    0   -   51;   %Adama I

2   437.55   12.9    0   -   120;      %Ayisha

3   -   15.8    0   -   153;     %Adama II

4   -   17.63   0   -   120;     %Ashegoda I

5   -   1.0256   0   14   16;  %Awash II and III Unit I

6   -   1.0256   0   14   16;  %Awash II and III Unit II

7   -   1.0256   0   14  16;  %Awash II and III Unit III

8   -   1.0256  0   14  16;  %Awash II and III Unit IV

9   265.76  15.75   0.06224 60  120;     %Bamza

10  429.78  7.133   0   20  30;  %Beles I

11  429.78  7.133   0   20  30; % Beles II

12  785.25  18.49   0   20  20;  %Corbetti I

13  785.25  18.49   0   100 100;     %Corbetti II

14  71.57   1.153   0   61.3    61.3;    %Gilgel Gibe I Unit I

15  71.57   1.153   0   61.3    61.3;   % Gilgel Gibe I Unit II

16  71.57   1.153   0   61.3    61.3;    %Gilgel Gibe I Unit III

17  -   2.0512  0   38.4    43; % Koka Unit I

18  255.94  15.75   0.06224 60  138;     %meikasedi

19  429.78  7.133   0   20  60;  %Omokuraz 1

20  429.78  7.133   0   40  60;  %Omokuraz 3
```

```
21   429.78   7.133    0    40   60;   %Omokuraz 4
22   –    2.0512   0    11   11.4;     %Tis Abay I Unit I
23   429.78   7.133    0    16   30;   %Wonji
24   785.25   16.19    0    5    7.3;     %AlutoLangano I
25   –    17.63    0    –    –;   %Ashegoda II
26   429.78   7.133    0    20   30; %Beles III
27   468.71   147.56   0    25   25; %EFW-Addis Ababa
28   429.78   7.133    0    10   31; %Fincha
29   28.375   0.5128   0    32   33.3;    %Fincha Unit I
30   28.375   0.5128   0    32   33.3;    %Fincha Unit II
31   28.375   0.5128   0    32   33.3;    %Fincha Unit III
32   28.375   0.5128   0    32.3    34; %Fincha Unit IV
33   8.625    0.435    0    354 400;     %GERD Unit I
34   8.625    0.435    0    354 400;     %GERD Unit II
35   8.625    0.435    0    354 400;     %GERD Unit III
36   8.625    0.435    0    354 400;     %GERD Unit IV
37   8.625    0.435    0    354 400;     %GERD Unit V
38   8.625    0.435    0    354 400;     %GERD Unit VI
39   8.625    0.435    0    354 400;     %GERD Unit VII
40   8.625    0.435    0    354 400;     %GERD Unit VIII
41   8.625    0.435    0    354 400;     %GERD Unit VX
42   8.625    0.435    0    354 400;     %GERD Unit X
43   8.625    0.435    0    354 400;     %GERD Unit XI
44   8.625    0.435    0    354 400;     %GERD Unit XII
45   8.625    0.435    0    354 400;     %GERD Unit XIII
46   8.625    0.435    0    354 400;     %GERD Unit XIV
47   8.625    0.435    0    351.25   375;     %GERD Unit XV
48   8.625    0.435    0    351.25   375;     %GERD Unit XVI
49   29.99    0.9075   0    107 107;     %Gilgel Gibe II Unit I
50   29.99    0.9075   0    107 107;     %Gilgel Gibe II Unit II
51   29.99    0.9075   0    107 107;     %Gilgel Gibe II Unit III
52   29.99    0.9075   0    107 107;     %Gilgel Gibe II Unit IV
53   15.8     0.569    0    106.7    187;     %Gilgel Gibe III Unit I
54   15.8     0.569    0    106.7    187;     %Gilgel Gibe III Unit II
```

```
55  15.8    0.569   0   106.7   187;    %Gilgel Gibe III Unit III
56  15.8    0.569   0   106.7   187;    %Gilgel Gibe III Unit IV
57  15.8    0.569   0   106.7   187;    %Gilgel Gibe III Unit V
58  15.8    0.569   0   106.7   187;    %Gilgel Gibe III Unit VI
59  15.8    0.569   0   106.7   187;    %Gilgel Gibe III Unit VII
60  15.8    0.569   0   106.7   187;    %Gilgel Gibe III Unit VIII
61  15.8    0.569   0   106.7   187;    %Gilgel Gibe III Unit VX
62  15.8    0.569   0   106.7   187;    %Gilgel Gibe III Unit X
63  429.78  7.133   0   16  26; %Kesem
64  35.4675 0.5128  0   38  38; %Melkawakena Unit I
65  35.4675 0.5128  0   38  38; %Melkawakena Unit II
66  35.4675 0.5128  0   38  38; %Melkawakena Unit III
67  35.4675 0.5128  0   38  38; %Melkawakena Unit IV
68  468.71  147.56  0   100 100;    %metehara
69  429.78  7.133   0   40  60; %Omokuraz 2
70  429.78  7.133   0   40  60; %Omokuraz 5
71  -   1.0256  0   2.5 2.5;    %Sor  I Unit I
72  -   1.0256  0   2.5 2.5;    %Sor  I Unit II
73  24.83   1.175   0   111 115;    %Tana beles Unit I
74  24.83   1.175   0   111 115;    %Tana beles Unit II
75  24.83   1.175   0   111 115;    %Tana beles Unit III
76  24.83   1.175   0   111 115;    %Tana beles Unit IV
77  27.21   1.4825  0   74.25   ;5; %Tekeze Unit I
78  27.21   1.4825  0   74.25   75; %Tekeze Unit II
79  27.21   1.4825  0   74.25   75; %Tekeze Unit III
80  27.21   1.4825  0   74.25   75; %Tekeze Unit IV
81  429.78  7.133   0   70  120;    %Tendaho
82  112.6   1.0256  0   34  36.8;   %Tis Abay II Unit I
83  112.6   1.0256  0   34  36.8;   %Tis Abay II Unit II
84  429.78  7.133   0   82  133;];  %Wolkayit
end;
```

MATLAB code for inserting variable demand

```
               PD=[ % time        Power Demand 1          11847.04155
```

2	11547.12606
3	23394.1676
4	11662.1314
5	11768.15114
6	11866.71086
7	12034.88594
8	12219.79114
9	12543.93396
10	13130.47914
11	13540.30971
12	13260.92285
13	12859.55294
14	12431.65383
15	12312.81593
16	12017.45115
17	12041.07891
18	11757.05716
19	11453.41733
20	11424.6024
21	11654.52416
22	12368.02728
23	12642.14203
24	11893.90157
25	11481.95197
26	11156.32106
27	10934.052
28	10755.1109
29	10773.80323
30	10899.48836
31	11087.42382
32	11539.29299
33	12891.70769
34	13329.38761
35	12991.57055

```
                                  36          12589.58508
                                  37          12000.16783
                                  38          11189.47913
                                  39          10532.63584
                                  40          10503.68776
                                  41          11531.41496
                                  42          11802.29333
                                  43          11586.99218
                                  44          11410.68723
                                  45          11221.63003
                                  46          11539.29299
                                  47          12891.70769
                                  48          13329.38761
                                           ];
```

MATLAB for EPGA solution method

```
% the computer aided exaplanations of equations (44)-(47) is
% clearly articlutae in muattion and crosover coding apart from
% the number of genration, itration, population and fitness is to be
% introduced using an optimization application
% function for mutation
function y=mutate(x,mu,VarMin,VarMax)
    nVar=numel(x);
    nmu=ceil(mu*nVar);
    i=randsample(nVar,nmu);
    sigma=0.1.*(VarMax-VarMin);
    y=x;
    y(i)=x(i)+sigma(i)*randn(size(i));
    y=max(y,VarMin);
    y=min(y,VarMax);
end;
% function for crossover
function [y0, y1 y2, y3 y4, y5]=Crossover(x0, x1,x2, x3, x4, x5,
gamma,VarMin,VarMax)
    alpha=unifrnd(-gamma,1+gamma,size(x1));
```

```
    y0=alpha.*x0+(1-alpha).*x1;
    y1=alpha.*x1+(1-alpha).*x2;
    y2=alpha.*x2+(1-alpha).*x3;
    y3=alpha.*x3+(1-alpha).*x4;
    y4=alpha.*x4+(1-alpha).*x5;
    y5=alpha.*x5+(1-alpha).*x1;
    y1=max(y1,VarMin);
    y2=min(y2,VarMax);
    y3=max(y3,VarMin);
    y4=min(y4,VarMax)
    y5=max(y5,VarMin);
    y2=min(y2,VarMax)
    y1=max(y1,VarMin);
    y3=min(y3,VarMax);
    y4=max(y4,VarMin);
    y5=min(y5,VarMax);
    y2=max(y2,VarMin);
    y4=min(y4,VarMax);
end;
```

Introducing Loss

```
        % define power generation loss PL from
        % F(p,i)=a(1,i)*x(p,i,:)^2+b(1,i)*x(p,i,:);
        for i=1:length(a)
            for j=1:length(a)
                PL=ploss+x(p,i,1)*B(i,j)*x(p,j,1);
            end
        end
        PL(p)=PL;
        delp(p)=abs(sum(x(p,:,1))-ploss-PD);
        error(p)=abs(delp(p));
        NE(p)=error(p)/Pd;
        fitness(p)=1/(1+NE(p));
        FT(p,:)=sum(F(p,:));
```

```
% fitnes function defintion and offspring reproduction

clear;

clc;

tic;

RE;

fitness;

    off_spring=[off_spring fitness' x(p,i) FT];

    % % off_spring=[off_spring fitness' x(p,i)];

    int_pop=[pop_bin;off_spring];

    % [m temp]=sort(int_pop(:,n_bits+1),'descend');

    % pop_bin=[];

    [m temp]=sort(int_pop(:,n_bits+1),'descend');

    pop_bin=[];

    for i=1:n_pop

        pop_bin(i,1:n_bits)=int_pop(temp(i),1:n_bits);

        fitness(i)=int_pop(temp(i),n_bits+1);

        p_gen(i,:)=int_pop(temp(i),n_bits+2:n_bits+3);

        FT(i,:)=int_pop(temp(i),n_bits+4);

    end

    fitness;

    pop_bin=[pop_bin fitness' p_gen FT];
```

MATLAB for HNN solution method

```
function varargout = hopfieldNetwork(varargin)
%      HOPFIELDNETWORK, by itself, creates a new HOPFIELDNETWORK or raises the
existing
%
15:45:38
% Begin initialization code
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @hopfieldNetwork_OpeningFcn, ...
                   'gui_OutputFcn',  @hopfieldNetwork_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end
if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
```

```
    gui_mainfcn(gui_State, varargin{:});
endT
% --- Executes just before hopfieldNetwork is made visible.
function hopfieldNetwork_OpeningFcn(hObject, ~, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to hopfieldNetwork (see VARARGIN)
% Choose default command line output for hopfieldNetwork
handles.output = hObject;
N = str2num(get(handles.imageSize,'string'));
handles.W = [];
handles.hPatternsDisplay = [];
% Update handles structure
guidata(hObject, handles);
% UIWAIT makes hopfieldNetwork wait for user response (see UIRESUME)
% uiwait(handles.figure1);
% --- Outputs from this function are returned to the command line.
function varargout = hopfieldNetwork_OutputFcn(~, ~, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Get default command line output from handles structure
varargout{1} = handles.output;
% --- Executes on button press in reset.
function reset_Callback(hObject, ~, handles)
% cleans all data and enables the change of the number of neurons used
    for n=1 : length(handles.hPatternsDisplay)
        delete(handles.hPatternsDisplay(n));
    end
    handles.hPatternsDisplay = [];
    set(handles.imageSize,'enable','on');
    handles.W = [];
    guidata(hObject, handles);
function imageSize_Callback(hObject, ~, ~)
% hObject    handle to imageSize (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
    num = get(hObject,'string');
    n = str2num(num);
    if isempty(n)
        num = '32';
        set(hObject,'string',num);
    end
    if n > 32
    end
% --- Executes during object creation, after setting all properties.
function imageSize_CreateFcn(hObject, eventdata, ~)
% hObject    handle to imageSize (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc
    set(hObject,'BackgroundColor','white');
```

```
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end
% --- Executes on button press in loadIm.
function loadIm_Callback(~, ~, handles)
    [fName, dirName] = uigetfile('*.bmp;*.tif;*.jpg;*.tiff');
    if fName
        set(handles.imageSize,'enable','off');
        cd(dirName);
        im = imread(fName);
        N = str2num(get(handles.imageSize,'string'));
        im = fixImage(im,N);
        imagesc(im,'Parent',handles.neurons);
        colormap('gray');
    end
% --- Executes on button press in train.
function train_Callback(hObject, ~, handles)

    Npattern = length(handles.hPatternsDisplay);
    if Npattern > 9
        msgbox('more then 10 paterns isn''t supported!','error');
        return
    end

    im = getimage(handles.neurons);
    N = get(handles.imageSize,'string');
    N = str2num(N);
    W = handles.W;  %weights vector
    avg = mean(im(:));   %removing the cross talk part
    if ~isempty(W)
        %W = W +( kron(im,im))/(N^2);
        W = W + ( kron(im-avg,im-avg))/(N^2)/avg/(1-avg);
    else
        % W = kron(im,im)/(N^2);
        W = ( kron(im-avg,im-avg))/(N^2)/avg/(1-avg);
    end
    % Erasing self weight
    ind = 1:N^2;
    f = find(mod(ind,N+1)==1);
    W(ind(f),ind(f)) = 0;

    handles.W = W;

    % Placing the new pattern in the figure...
    xStart = 0.01;
    xEnd = 0.99;
    height = 0.65;
    width = 0.09;
    xLength = xEnd-xStart;
    xStep = xLength/10;
    offset = 4-ceil(Npattern/2);
    offset = max(offset,0);
    y = 0.1;

    if Npattern > 0
        for n=1 : Npattern
```

```
            x = xStart+(n+offset-1)*xStep;
            h = handles.hPatternsDisplay(n);
            set(h,'units','normalized');
            set(h,'position',[x y width height]);
        end
        x = xStart+(n+offset)*xStep;
        h = axes('units','normalized','position',[x y width height]);
        handles.hPatternsDisplay(n+1) = h;
        imagesc(im,'Parent',h);
    else
        x = xStart+(offset)*xStep;
        h = axes('units','normalized','position',[x y width height]);
        handles.hPatternsDisplay = h;
    end

    imagesc(im,'Parent',h);
    set(h,
'YTick',[],'XTick',[],'XTickMode','manual','Parent',handles.learnedPaterns);

    guidata(hObject, handles);
% --- Executes on button press
function addNoise_Callback(hObject, eventdata, handles)
    im = getimage(handles.neurons);
    % N = get(handles.imageSize,'string');
    % N = floor(str2num(N)/2)+1;
    noisePercent = get( handles.noiseAmount, 'value' );
    N = round( length(im(:))* noisePercent );
    N = max(N,1);   %minimum change one neuron
    ind = ceil(rand(N,1)*length(im(:)));
%    im(ind) = -1*im(ind); %!!!!
    im(ind) = ~im(ind);
    imagesc(im,'Parent',handles.neurons);
    colormap('gray');

function run_Callback(hObject, ~, handles)
    im = getimage(handles.neurons);
    [rows, cols] = size(im);
    if rows ~= cols
        msgbox('I don''t support non square images','error');
        return;
    end
    N = rows;
    W = handles.W;
    if isempty(W)
        msgbox('No train data - doing nothing!','error');
        return;
    end
    %figure; imagesc(W)
    mat = repmat(im,N,N);
    mat = mat.*W;
    mat = im2col(mat,[N,N],'distinct');
    networkResult = sum(mat);
    networkResult = reshape(networkResult,N,N);
    im = fixImage(networkResult,N);
    imagesc(im,'Parent',handles.neurons);
function im = fixImage(im,N)
```

```
%    if isrgb(im)
    if length( size(im) ) == 3
        im = rgb2gray(im);
    end
    im = double(im);
    m = min(im(:));
    M = max(im(:));
    im = (im-m)/(M-m);  %normelizing the image
    im = imresize(im,[N N],'bilinear');
    %im = (im > 0.5)*2-1;    %changing image values to -1 & 1
    im = (im > 0.5);    %changing image values to 0 & 1
% --- Executes on slider movement.
function noiseAmount_Callback(hObject, ~, handles)
% hObject    handle to noiseAmount (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
    percent = get(hObject,'value');
    percent = round(percent*100);
    set(handles.noisePercent,'string',num2str(percent));
% Hints: get(hObject,'Value') returns position of slider
%        get(hObject,'Min') and get(hObject,'Max') to determine range of slider
% --- Executes during object creation, after setting all properties.
function noiseAmount_CreateFcn(hObject, ~, ~)
% hObject    handle to noiseAmount (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
% Hint: slider controls usually have a light gray background, change
%       'usewhitebg' to 0 to use default.  See ISPC and COMPUTER.
usewhitebg = 1;
if usewhitebg
    set(hObject,'BackgroundColor',[.9 .9 .9]);
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end
```

Appendix B

Basic Data and Characteristics

Generators : Parameters for the two-axis model of the synchronous machines are shown in Tables as follows. All values are given on the same system base MVA

Unit No.	H	Ra	x'd	x'q	xd	xq	T'do	T'qo	xl
1	500.0	0	0.006	0.008	0.02	0.019	7.0	0.7	0.003
2	30.3	0	0.0697	0.170	0.295	0.282	6.56	1.5	0.035
3	35.8	0	0.0531	0.0876	0.2495	0.237	5.7	1.5	0.0304
4	28.6	0	0.0436	0.166	0.262	0.258	5.69	1.5	0.0295
5	26.0	0	0.132	0.166	0.67	0.62	5.4	0.44	0.054
6	34.8	0	0.05	0.0814	0.254	0.241	7.3	0.4	0.0224
7	26.4	0	0.049	0.186	0.295	0.292	5.66	1.5	0.0322
8	24.3	0	0.057	0.0911	0.290	0.280	6.7	0.41	0.028
9	34.5	0	0.057	0.0587	0.2106	0.205	4.79	1.96	0.0298
10	42.0	0	0.031	0.008	0.1	0.069	10.2	0.0	0.0125

Lines/Transformers: The network data for this system is shown in the Table below. All values are given on the same system base MVA.

Line Data					Transformer Tap	
From Bus	To Bus	R	X	B	Magnitude	Angle
1	2	0.0035	0.0411	0.6987	0.000	0.00
1	39	0.0010	0.0250	0.7500	0.000	0.00
2	3	0.0013	0.0151	0.2572	0.000	0.00
2	25	0.0070	0.0086	0.1460	0.000	0.00
3	4	0.0013	0.0213	0.2214	0.000	0.00
3	18	0.0011	0.0133	0.2138	0.000	0.00
4	5	0.0008	0.0128	0.1342	0.000	0.00
4	14	0.0008	0.0129	0.1382	0.000	0.00
5	6	0.0002	0.0026	0.0434	0.000	0.00
5	8	0.0008	0.0112	0.1476	0.000	0.00
6	7	0.0006	0.0092	0.1130	0.000	0.00
6	11	0.0007	0.0082	0.1389	0.000	0.00
7	8	0.0004	0.0046	0.0780	0.000	0.00
8	9	0.0023	0.0363	0.3804	0.000	0.00
9	39	0.0010	0.0250	1.2000	0.000	0.00

10	11	0.0004	0.0043	0.0729	0.000	0.00
10	13	0.0004	0.0043	0.0729	0.000	0.00
13	14	0.0009	0.0101	0.1723	0.000	0.00
14	15	0.0018	0.0217	0.3660	0.000	0.00
15	16	0.0009	0.0094	0.1710	0.000	0.00
16	17	0.0007	0.0089	0.1342	0.000	0.00
16	19	0.0016	0.0195	0.3040	0.000	0.00
16	21	0.0008	0.0135	0.2548	0.000	0.00
16	24	0.0003	0.0059	0.0680	0.000	0.00
17	18	0.0007	0.0082	0.1319	0.000	0.00
17	27	0.0013	0.0173	0.3216	0.000	0.00
21	22	0.0008	0.0140	0.2565	0.000	0.00
22	23	0.0006	0.0096	0.1846	0.000	0.00
23	24	0.0022	0.0350	0.3610	0.000	0.00
25	26	0.0032	0.0323	0.5130	0.000	0.00
26	27	0.0014	0.0147	0.2396	0.000	0.00
26	28	0.0043	0.0474	0.7802	0.000	0.00
26	29	0.0057	0.0625	1.0290	0.000	0.00
28	29	0.0014	0.0151	0.2490	0.000	0.00
12	11	0.0016	0.0435	0.0000	1.006	0.00
12	13	0.0016	0.0435	0.0000	1.006	0.00
6	31	0.0000	0.0250	0.0000	1.070	0.00
10	32	0.0000	0.0200	0.0000	1.070	0.00
19	33	0.0007	0.0142	0.0000	1.070	0.00
20	34	0.0009	0.0180	0.0000	1.009	0.00

Power and Voltage Set points: All values are given on the same system base MVA. Note that generator 2 is the swing node.

Bus	Type	Voltage [PU]	Load		Generator		
			MW	MVar	MW	MVar	Unit No.
1	PQ	-	0.0	0.0	0.0	0.0	
2	PQ	-	0.0	0.0	0.0	0.0	
3	PQ	-	322.0	2.4	0.0	0.0	
4	PQ	-	500.0	184.0	0.0	0.0	
5	PQ	-	0.0	0.0	0.0	0.0	
6	PQ	-	0.0	0.0	0.0	0.0	
7	PQ	-	233.8	84.0	0.0	0.0	
8	PQ	-	522.0	176.0	0.0	0.0	
9	PQ	-	0.0	0.0	0.0	0.0	
10	PQ	-	0.0	0.0	0.0	0.0	
11	PQ	-	0.0	0.0	0.0	0.0	

12	PQ	-	7.5	88.0	0.0	0.0	
13	PQ	-	0.0	0.0	0.0	0.0	
14	PQ	-	0.0	0.0	0.0	0.0	
15	PQ	-	320.0	153.0	0.0	0.0	
16	PQ	-	329.0	32.3	0.0	0.0	
17	PQ	-	0.0	0.0	0.0	0.0	
18	PQ	-	158.0	30.0	0.0	0.0	
19	PQ	-	0.0	0.0	0.0	0.0	
20	PQ	-	628.0	103.0	0.0	0.0	
21	PQ	-	274.0	115.0	0.0	0.0	
22	PQ	-	0.0	0.0	0.0	0.0	
23	PQ	-	247.5	84.6	0.0	0.0	
24	PQ	-	308.6	-92.0	0.0	0.0	
25	PQ	-	224.0	47.2	0.0	0.0	
26	PQ	-	139.0	17.0	0.0	0.0	
27	PQ	-	281.0	75.5	0.0	0.0	
28	PQ	-	206.0	27.6	0.0	0.0	
29	PQ	-	283.5	26.9	0.0	0.0	
30	PV	1.0475	0.0	0.0	250.0	-	Gen10
31	PV	0.9820	9.2	4.6	-	-	Gen2
32	PV	0.9831	0.0	0.0	650.0	-	Gen3
33	PV	0.9972	0.0	0.0	632.0	-	Gen4
34	PV	1.0123	0.0	0.0	508.0	-	Gen5
35	PV	1.0493	0.0	0.0	650.0	-	Gen6
36	PV	1.0635	0.0	0.0	560.0	-	Gen7
37	PV	1.0278	0.0	0.0	540.0	-	Gen8
38	PV	1.0265	0.0	0.0	830.0	-	Gen9
39	PV	1.0300	1104.0	250.0	1000.0	-	Gen1

Appendix C

IEEE 118-bus, 54-unit, 24-hour system

Unit and Network Data

TABLE 1 GENERATOR DATA

U	Unit Cost Coefficients			Pmax (MW)	Pmin (MW)	Qmax (MVAR)
	a (MBtu)	b (MBtu/ MW)	c (MBtu/MW^2)			
1	31.67	26.24	0.06966	30	5	300
2	31.67	26.24	0.06966	30	5	50
3	31.67	26.24	0.06966	30	5	300
4	6.78	12.89	0.01088	300	150	200
5	6.78	12.89	0.01088	300	100	120

6	31.67	26.24	0.06966	30	10	30
7	10.15	17.82	0.0128	100	25	50
8	31.67	26.24	0.06966	30	5	24
9	31.67	26.24	0.06966	30	5	300
10	6.78	12.89	0.01088	300	100	140
11	32.96	10.76	0.003	350	100	1000
12	31.67	26.24	0.06966	30	8	300
13	31.67	26.24	0.06966	30	8	300
14	10.15	17.82	0.0128	100	25	42
15	31.67	26.24	0.06966	30	8	24
16	10.15	17.82	0.0128	100	25	24
17	31.67	26.24	0.06966	30	8	300
18	31.67	26.24	0.06966	30	8	300
19	10.15	17.82	0.0128	100	25	100
20	28	12.33	0.0024	250	50	210
21	28	12.33	0.0024	250	50	300
22	10.15	17.82	0.0128	100	25	23
23	10.15	17.82	0.0128	100	25	15
24	39	13.29	0.0044	200	50	180
25	39	13.29	0.0044	200	50	300
26	10.15	17.82	0.0128	100	25	20
27	64.16	8.339	0.01059	420	100	200
28	64.16	8.339	0.01059	420	100	200
29	6.78	12.89	0.01088	300	80	99999
30	74.33	15.47	0.04592	80	30	32
31	31.67	26.24	0.06966	30	10	100
32	31.67	26.24	0.06966	30	5	100
33	17.95	37.7	0.0283	20	5	9
34	10.15	17.82	0.0128	100	25	23
35	10.15	17.82	0.0128	100	25	70
36	6.78	12.89	0.01088	300	150	280
37	10.15	17.82	0.0128	100	25	9900
38	31.67	26.24	0.06966	30	10	23
39	32.96	10.76	0.003	300	100	1000
40	6.78	12.89	0.01088	200	50	300
41	17.95	37.7	0.0283	20	8	300
42	58.81	22.94	0.00977	50	20	100
43	6.78	12.89	0.01088	300	100	9

44	6.78	12.89	0.01088	300	100	100
45	6.78	12.89	0.01088	300	100	155
46	17.95	37.7	0.0283	20	8	40
47	10.15	17.82	0.0128	100	25	23
48	10.15	17.82	0.0128	100	25	23
49	17.95	37.7	0.0283	20	8	200
50	58.81	22.94	0.00977	50	25	23
51	10.15	17.82	0.0128	100	25	1000
52	10.15	17.82	0.0128	100	25	1000
53	10.15	17.82	0.0128	100	25	200
54	58.81	22.94	0.00977	50	25	1000

U	Qmin (MVAR)	Ini. State (h)	Min Off (h)	Min On (h)	Ramp (MW/h)	Start Up (MBtu)	Fuel Price ($/ MBtu)
1	-300	1	1	1	15	40	1
2	-13	1	1	1	15	40	1
3	-300	1	1	1	15	40	1
4	-147	8	8	8	150	440	1
5	-35	8	8	8	150	110	1
6	-10	1	1	1	15	40	1
7	-16	5	5	5	50	50	1
8	-8	1	1	1	15	40	1
9	-300	1	1	1	15	40	1
10	-47	8	8	8	150	100	1
11	-1000	8	8	8	175	100	1
12	-300	1	1	1	15	40	1
13	-300	1	1	1	15	40	1
14	-14	5	5	5	50	50	1
15	-8	1	1	1	15	40	1
16	-8	5	5	5	50	50	1
17	-300	1	1	1	15	40	1
18	-300	1	1	1	15	40	1
19	-100	5	5	5	50	59	1
20	-85	8	8	8	125	100	1
21	-300	8	8	8	125	100	1
22	-8	5	5	5	50	50	1
23	-8	5	5	5	50	50	1

24	-60	10	8	8	100	100	1
25	-100	10	8	8	100	100	1
26	-20	5	5	5	50	50	1
27	-67	10	10	10	210	250	1
28	-67	10	10	10	210	250	1
29	-99999	10	8	8	150	100	1
30	-10	4	4	4	40	45	1
31	-100	1	1	1	15	40	1
32	-100	1	1	1	15	40	1
33	-6	1	1	1	10	30	1
34	-8	5	5	5	50	50	1
35	-20	5	5	5	50	50	1
36	-165	10	8	8	150	440	1
37	-9900	5	5	5	50	50	1
38	-8	1	1	1	15	40	1
39	-100	10	8	8	150	440	1
40	-210	10	8	8	100	400	1
41	-300	1	1	1	10	30	1
42	-100	1	1	1	25	45	1
43	-3	8	8	8	150	100	1
44	-100	8	8	8	150	100	1
45	-50	8	8	8	150	110	1
46	-15	1	1	1	10	30	1
47	-8	5	5	5	50	50	1
48	-8	5	5	5	50	50	1
49	-200	1	1	1	10	30	1
50	-8	2	2	2	25	45	1
51	-100	5	5	5	50	50	1
52	-100	5	5	5	50	50	1
53	-100	5	5	5	50	50	1
54	-1000	2	2	2	25	45	1

TABLE 2 BUS DATA

Bus No.	Voltage-Max (pu)	Voltage-Min (pu)
1	1.05	0.94
2	1.06	0.95
3	1.06	0.95
4	1.09	0.99
5	1.09	0.99

6	1.09	0.97
7	1.09	0.97
8	1.09	0.98
9	1.09	0.98
10	1.09	0.98
11	1.08	0.97
12	1.09	0.98
13	1.05	0.95
14	1.07	0.98
15	1.05	0.98
16	1.07	0.98
17	1.09	0.98
18	1.07	0.98
19	1.06	0.98
20	1.04	0.96
21	1.03	0.95
22	1.04	0.97
23	1.09	0.98
24	1.09	0.98
25	1.09	0.98
26	1.09	0.98
27	1.09	0.96
28	1.08	0.94
29	1.08	0.93
30	1.06	0.98
31	1.09	0.94
32	1.08	0.97
33	1.04	0.96
34	1.08	0.97
35	1.08	0.96
36	1.08	0.96
37	1.09	0.98
38	1.04	0.95
39	1.09	0.93
40	1.09	0.93
41	1.09	0.93
42	1.09	0.92
43	1.06	0.96
44	1.06	0.97
45	1.06	0.98
46	1.09	0.98
47	1.09	0.98
48	1.09	0.98
49	1.09	0.98
50	1.09	0.99
51	1.07	0.97
52	1.06	0.97
53	1.06	0.96
54	1.09	0.97

55	1.09	0.97
56	1.09	0.97
57	1.08	0.98
58	1.07	0.97
59	1.09	0.98
60	1.09	0.99
61	1.09	0.99
62	1.09	0.98
63	1.06	0.96
64	1.07	0.98
65	1.07	0.98
66	1.09	0.98
67	1.09	0.98
68	1.08	0.98
69	1.09	0.98
70	1.06	0.98
71	1.06	0.99
72	1.09	0.99
73	1.06	0.99
74	1.03	0.93
75	1.04	0.94
76	1.02	0.93
77	1.08	0.98
78	1.07	0.99
79	1.07	0.99
80	1.09	0.99
81	1.07	0.98
82	1.09	0.98
83	1.07	0.99
84	1.03	0.96
85	1.02	0.96
86	0.96	0.93
87	1.09	0.98
88	1.06	0.98
89	1.09	0.98
90	1.09	0.98
91	1.09	0.98
92	1.09	0.98
93	1.08	0.98
94	1.07	0.98
95	1.05	0.98
96	1.07	0.98
97	1.08	0.98
98	1.08	0.98
99	1.09	0.98
100	1.09	0.98
101	1.08	0.98
102	1.09	0.98
103	1.09	0.98

104	1.08	0.99
105	1.08	0.98
106	1.07	0.96
107	1.06	0.94
108	1.08	0.98
109	1.08	0.98
110	1.09	0.97
111	1.09	0.97
112	1.09	0.97
113	1.09	0.98
114	1.08	0.96
115	1.08	0.96
116	1.09	0.98
117	1.06	0.95
118	1.03	0.93

TABLE 3 TRANSMISSION LINE DATA

Line No.	From Bus	To Bus	Circuit ID	R (pu)	X (pu)	B (pu)	Flow Limit (MW)
1	1	2	1	0.0303	0.0999	0.0254	175
2	1	3	1	0.0129	0.0424	0.01082	175
3	4	5	1	0.00176	0.00798	0.0021	500
4	3	5	1	0.0241	0.108	0.0284	175
5	5	6	1	0.0119	0.054	0.01426	175
6	6	7	1	0.00459	0.0208	0.0055	175
7	8	9	1	0.00244	0.0305	1.162	500
8	8	5	1	0	0.0267	0	500
9	9	10	1	0.00258	0.0322	1.23	500
10	4	11	1	0.0209	0.0688	0.01748	175
11	5	11	1	0.0203	0.0682	0.01738	175
12	11	12	1	0.00595	0.0196	0.00502	175
13	2	12	1	0.0187	0.0616	0.01572	175
14	3	12	1	0.0484	0.16	0.0406	175
15	7	12	1	0.00862	0.034	0.00874	175
16	11	13	1	0.02225	0.0731	0.01876	175
17	12	14	1	0.0215	0.0707	0.01816	175
18	13	15	1	0.0744	0.2444	0.06268	175
19	14	15	1	0.0595	0.195	0.0502	175
20	12	16	1	0.0212	0.0834	0.0214	175
21	15	17	1	0.0132	0.0437	0.0444	500
22	16	17	1	0.0454	0.1801	0.0466	175
23	17	18	1	0.0123	0.0505	0.01298	175
24	18	19	1	0.01119	0.0493	0.01142	175
25	19	20	1	0.0252	0.117	0.0298	175
26	15	19	1	0.012	0.0394	0.0101	175
27	20	21	1	0.0183	0.0849	0.0216	175
28	21	22	1	0.0209	0.097	0.0246	175
29	22	23	1	0.0342	0.159	0.0404	175

30	23	24	1	0.0135	0.0492	0.0498	175
31	23	25	1	0.0156	0.08	0.0864	500
32	26	25	1	0	0.0382	0	500
33	25	27	1	0.0318	0.163	0.1764	500
34	27	28	1	0.01913	0.0855	0.0216	175
35	28	29	1	0.0237	0.0943	0.0238	175
36	30	17	1	0	0.0388	0	500
37	8	30	1	0.00431	0.0504	0.514	175
38	26	30	1	0.00799	0.086	0.908	500
39	17	31	1	0.0474	0.1563	0.0399	175
40	29	31	1	0.0108	0.0331	0.0083	175
41	23	32	1	0.0317	0.1153	0.1173	140
42	31	32	1	0.0298	0.0985	0.0251	175
43	27	32	1	0.0229	0.0755	0.01926	175
44	15	33	1	0.038	0.1244	0.03194	175
45	19	34	1	0.0752	0.247	0.0632	175
46	35	36	1	0.00224	0.0102	0.00268	175
47	35	37	1	0.011	0.0497	0.01318	175
48	33	37	1	0.0415	0.142	0.0366	175
49	34	36	1	0.00871	0.0268	0.00568	175
50	34	37	1	0.00256	0.0094	0.00984	500
51	38	37	1	0	0.0375	0	500
52	37	39	1	0.0321	0.106	0.027	175
53	37	40	1	0.0593	0.168	0.042	175
54	30	38	1	0.00464	0.054	0.422	175
55	39	40	1	0.0184	0.0605	0.01552	175
56	40	41	1	0.0145	0.0487	0.01222	175
57	40	42	1	0.0555	0.183	0.0466	175
58	41	42	1	0.041	0.135	0.0344	175
59	43	44	1	0.0608	0.2454	0.06068	175
60	34	43	1	0.0413	0.1681	0.04226	175
61	44	45	1	0.0224	0.0901	0.0224	175
62	45	46	1	0.04	0.1356	0.0332	175
63	46	47	1	0.038	0.127	0.0316	175
64	46	48	1	0.0601	0.189	0.0472	175
65	47	49	1	0.0191	0.0625	0.01604	175
66	42	49	1	0.0715	0.323	0.086	175
67	42	49	2	0.0715	0.323	0.086	175
68	45	49	1	0.0684	0.186	0.0444	175
69	48	49	1	0.0179	0.0505	0.01258	175
70	49	50	1	0.0267	0.0752	0.01874	175
71	49	51	1	0.0486	0.137	0.0342	175
72	51	52	1	0.0203	0.0588	0.01396	175
73	52	53	1	0.0405	0.1635	0.04058	175
74	53	54	1	0.0263	0.122	0.031	175
75	49	54	1	0.073	0.289	0.0738	175
76	49	54	2	0.0869	0.291	0.073	175
77	54	55	1	0.0169	0.0707	0.0202	175
78	54	56	1	0.00275	0.00955	0.00732	175

79	55	56	1	0.00488	0.0151	0.00374	175
80	56	57	1	0.0343	0.0966	0.0242	175
81	50	57	1	0.0474	0.134	0.0332	175
82	56	58	1	0.0343	0.0966	0.0242	175
83	51	58	1	0.0255	0.0719	0.01788	175
84	54	59	1	0.0503	0.2293	0.0598	175
85	56	59	1	0.0825	0.251	0.0569	175
86	56	59	2	0.0803	0.239	0.0536	175
87	55	59	1	0.04739	0.2158	0.05646	175
88	59	60	1	0.0317	0.145	0.0376	175
89	59	61	1	0.0328	0.15	0.0388	175
90	60	61	1	0.00264	0.0135	0.01456	500
91	60	62	1	0.0123	0.0561	0.01468	175
92	61	62	1	0.00824	0.0376	0.0098	175
93	63	59	1	0	0.0386	0	500
94	63	64	1	0.00172	0.02	0.216	500
95	64	61	1	0	0.0268	0	500
96	38	65	1	0.00901	0.0986	1.046	500
97	64	65	1	0.00269	0.0302	0.38	500
98	49	66	1	0.018	0.0919	0.0248	500
99	49	66	2	0.018	0.0919	0.0248	500
100	62	66	1	0.0482	0.218	0.0578	175
101	62	67	1	0.0258	0.117	0.031	175
102	65	66	1	0	0.037	0	500
103	66	67	1	0.0224	0.1015	0.02682	175
104	65	68	1	0.00138	0.016	0.638	500
105	47	69	1	0.0844	0.2778	0.07092	175
106	49	69	1	0.0985	0.324	0.0828	175
107	68	69	1	0	0.037	0	500
108	69	70	1	0.03	0.127	0.122	500
109	24	70	1	0.00221	0.4115	0.10198	175
110	70	71	1	0.00882	0.0355	0.00878	175
111	24	72	1	0.0488	0.196	0.0488	175
112	71	72	1	0.0446	0.18	0.04444	175
113	71	73	1	0.00866	0.0454	0.01178	175
114	70	74	1	0.0401	0.1323	0.03368	175
115	70	75	1	0.0428	0.141	0.036	175
116	69	75	1	0.0405	0.122	0.124	500
117	74	75	1	0.0123	0.0406	0.01034	175
118	76	77	1	0.0444	0.148	0.0368	175
119	69	77	1	0.0309	0.101	0.1038	175
120	75	77	1	0.0601	0.1999	0.04978	175
121	77	78	1	0.00376	0.0124	0.01264	175
122	78	79	1	0.00546	0.0244	0.00648	175
123	77	80	1	0.017	0.0485	0.0472	500
124	77	80	2	0.0294	0.105	0.0228	500
125	79	80	1	0.0156	0.0704	0.0187	175
126	68	81	1	0.00175	0.0202	0.808	500
127	81	80	1	0	0.037	0	500

128	77	82	1	0.0298	0.0853	0.08174	200
129	82	83	1	0.0112	0.03665	0.03796	200
130	83	84	1	0.0625	0.132	0.0258	175
131	83	85	1	0.043	0.148	0.0348	175
132	84	85	1	0.0302	0.0641	0.01234	175
133	85	86	1	0.035	0.123	0.0276	500
134	86	87	1	0.02828	0.2074	0.0445	500
135	85	88	1	0.02	0.102	0.0276	175
136	85	89	1	0.0239	0.173	0.047	175
137	88	89	1	0.0139	0.0712	0.01934	500
138	89	90	1	0.0518	0.188	0.0528	500
139	89	90	2	0.0238	0.0997	0.106	500
140	90	91	1	0.0254	0.0836	0.0214	175
141	89	92	1	0.0099	0.0505	0.0548	500
142	89	92	2	0.0393	0.1581	0.0414	500
143	91	92	1	0.0387	0.1272	0.03268	175
144	92	93	1	0.0258	0.0848	0.0218	175
145	92	94	1	0.0481	0.158	0.0406	175
146	93	94	1	0.0223	0.0732	0.01876	175
147	94	95	1	0.0132	0.0434	0.0111	175
148	80	96	1	0.0356	0.182	0.0494	175
149	82	96	1	0.0162	0.053	0.0544	175
150	94	96	1	0.0269	0.0869	0.023	175
151	80	97	1	0.0183	0.0934	0.0254	175
152	80	98	1	0.0238	0.108	0.0286	175
153	80	99	1	0.0454	0.206	0.0546	200
154	92	100	1	0.0648	0.295	0.0472	175
155	94	100	1	0.0178	0.058	0.0604	175
156	95	96	1	0.0171	0.0547	0.01474	175
157	96	97	1	0.0173	0.0885	0.024	175
158	98	100	1	0.0397	0.179	0.0476	175
159	99	100	1	0.018	0.0813	0.0216	175
160	100	101	1	0.0277	0.1262	0.0328	175
161	92	102	1	0.0123	0.0559	0.01464	175
162	101	102	1	0.0246	0.112	0.0294	175
163	100	103	1	0.016	0.0525	0.0536	500
164	100	104	1	0.0451	0.204	0.0541	175
165	103	104	1	0.0466	0.1584	0.0407	175
166	103	105	1	0.0535	0.1625	0.0408	175
167	100	106	1	0.0605	0.229	0.062	175
168	104	105	1	0.00994	0.0378	0.00986	175
169	105	106	1	0.014	0.0547	0.01434	175
170	105	107	1	0.053	0.183	0.0472	175
171	105	108	1	0.0261	0.0703	0.01844	175
172	106	107	1	0.053	0.183	0.0472	175
173	108	109	1	0.0105	0.0288	0.0076	175
174	103	110	1	0.03906	0.1813	0.0461	175
175	109	110	1	0.0278	0.0762	0.0202	175
176	110	111	1	0.022	0.0755	0.02	175

177	110	112	1	0.0247	0.064	0.062	175
178	17	113	1	0.00913	0.0301	0.00768	175
179	32	113	1	0.0615	0.203	0.0518	500
180	32	114	1	0.0135	0.0612	0.01628	175
181	27	115	1	0.0164	0.0741	0.01972	175
182	114	115	1	0.0023	0.0104	0.00276	175
183	68	116	1	0.00034	0.00405	0.164	500
184	12	117	1	0.0329	0.14	0.0358	175
185	75	118	1	0.0145	0.0481	0.01198	175
186	76	118	1	0.0164	0.0544	0.01356	175

TABLE 4 TAP CHANGING TRANSFORMER DATA

Transformer No.	From Bus	To Bus	Circuit ID	Tap Initial	Tap Max	Tap Min	Angle Initial	Angle Max	Angle Min
1	8	5	1	0.985	0	0	0	0	0
2	26	25	1	0.96	0	0	0	0	0
3	30	17	1	0.96	0	0	0	0	0
4	38	37	1	0.935	0	0	0	0	0
5	63	59	1	0.96	0	0	0	0	0
6	64	61	1	0.985	0	0	0	0	0
7	65	66	1	0.935	0	0	0	0	0
8	68	69	1	0.935	0	0	0	0	0
9	81	80	1	0.935	0	0	3.57	-15	15

TABLE 5 HOURLY LOAD AND ANCILLARY SERVICES

Hour	Real Load (MW)	Reactive Load (MVAR)	Regulation Down (MW)	Regulation Up (MW)	Spinning Reserve (MW)	Non-spinning Reserve (MW)	Operating Reserve (MW)
1	4200	1623.47	42	42	84	84	210
2	3960	1530.70	39.6	39.6	79.2	79.2	198
3	3480	1345.16	34.8	34.8	69.6	69.6	174
4	2400	927.70	24	24	48	48	120
5	3000	1159.62	30	30	60	60	150
6	3600	1391.54	36	36	72	72	180
7	4200	1623.47	42	42	84	84	210
8	4680	1809.01	46.8	46.8	93.6	93.6	234
9	4920	1901.78	49.2	49.2	98.4	98.4	246
10	5280	2040.93	52.8	52.8	105.6	105.6	264
11	5340	2064.12	53.4	53.4	106.8	106.8	267
12	5040	1948.16	50.4	50.4	100.8	100.8	252
13	4800	1855.39	48	48	96	96	240
14	4560	1762.62	45.6	45.6	91.2	91.2	228
15	5280	2040.93	52.8	52.8	105.6	105.6	264

16	5400	2087.31	54	54	108	108	270
17	5100	1971.35	51	51	102	102	255
18	5340	2064.12	53.4	53.4	106.8	106.8	267
19	5640	2180.08	56.4	56.4	112.8	112.8	282
20	5880	2272.85	58.8	58.8	117.6	117.6	294
21	6000	2319.24	60	60	120	120	300
22	5400	2087.31	54	54	108	108	270
23	5220	2017.74	52.2	52.2	104.4	104.4	261
24	4920	1901.78	49.2	49.2	98.4	98.4	246

TABLE 6 BUS LOAD DISTRIBUTION PROFILE

Bus No	Pd (MW)	Qd (MVAR)
1	54.14	8.66
2	21.23	9.55
3	41.4	10.62
4	31.85	12.74
6	55.2	23.35
7	20.17	2.12
11	74.31	24.42
12	49.89	10.62
13	36.09	16.99
14	14.86	1.06
15	95.54	31.85
16	26.54	10.62
17	11.68	3.18
18	63.69	36.09
19	47.77	26.54
20	19.11	3.18
21	14.86	8.49
22	10.62	5.31
23	7.43	3.18
27	65.82	13.8
28	18.05	7.43
29	25.48	4.25
31	45.65	28.66
32	62.63	24.42
33	24.42	9.55
34	62.63	27.6
35	35.03	9.55
36	32.91	18.05
39	27	11
40	20	23
41	37	10
42	37	23
43	18	7
44	16	8
45	53	22

46	28	10
47	34	0
48	20	11
49	87	30
50	17	4
51	17	8
52	18	5
53	23	11
54	113	32
55	63	22
56	84	18
57	12	3
58	12	3
59	277	113
60	78	3
62	77	14
66	39	18
67	28	7
70	66	20
74	68	27
75	47	11
76	68	36
77	61	28
78	71	26
79	39	32
80	130	26
82	54	27
83	20	10
84	11	7
85	24	15
86	21	10
88	48	10
90	78	42
92	65	10
93	12	7
94	30	16
95	42	31
96	38	15
97	15	9
98	34	8
100	37	18
101	22	15
102	5	3
103	23	16
104	38	25
105	31	26
106	43	16
107	28	12
108	2	1

109	8	3
110	39	30
112	25	13
114	8.49	3.18
115	23.35	7.43
117	21.23	8.49
118	33	15

TABLE 7 HOURLY ANCILLARY SERVICES DISPATCH

Hour	Regulation Up (MW)	Spinning Reserve (MW)	Non-spinning Reserve (MW)	Operating Reserve (MW)
1	68.8	260	91.17	0
2	76.8	275.2	44.05	0
3	76.8	271.19	0	0
4	96.8	143.2	0	0
5	76.8	223.18	0	0
6	76.8	275.2	7.96	0
7	68.8	260	91.17	0
8	98.8	363.1	6.07	0
9	98.8	312	81.19	0
10	98.8	312	117.27	0
11	98.8	312	123.21	0
12	98.8	312	93.19	0
13	98.8	325.34	55.89	0
14	98.8	357.2	0	0
15	100.8	320	107.27	0
16	100.8	320	119.22	0
17	100.8	320	89.16	0
18	100.8	320	113.24	0
19	80	320	164.04	0
20	80	320	187.97	0
21	80.99	320	199	0
22	100.8	320	119.24	0
23	100.8	320	101.26	0
24	98.8	312	81.19	0

Power plant	Installed capacity (MW)	Dependable capacity (MW)	Capacity Factor (%)	Capital Cost ($/Kw)	O&M Cost ($/MWh)	Fuel Cost ($/MWh)	Type of Resource
Adama I	51	–	30	–	15.5	0	wind
Ayisha	120	–	34	437.55	12.9	0	wind
Adama II	153	–	32	–	15.8	0	wind
Ashegoda I	120	–	21	–	17.63	0	wind

Awash II and III Unit I	16	14	65.86	–	1.0256	0	hydro
Awash II and III Unit II	16	14	65.86	–	1.0256	0	hydro
Awash II and III Unit III	16	14	65.86	–	1.0256	0	hydro
Awash II and III Unit IV	16	14	65.86	–	1.0256	0	hydro
Bamza	120	60		265.76	15.75	62.24	bgass
Beles I	30	20		429.78	7.133	0	bgass
Beles II	30	20		429.78	7.133	0	bgass
Corbetti I	20	20	90	785.25	18.49	0	geothermal
Corbetti II	100	100	90	785.25	18.49	0	geothermal
Gilgel Gibe I Unit I	61.3	61.3	48.08	71.57	1.153	0	hydro
Gilgel Gibe I Unit II	61.3	61.3	48.08	71.57	1.153	0	hydro
Gilgel Gibe I Unit III	61.3	61.3	48.08	71.57	1.153	0	hydro
Koka Unit I	43	38.4	35.58	–	2.0512	0	hydro
meikasedi	138	60		255.94	15.75	62.24	bgass
Omokuraz 1	60	20		429.78	7.133	0	bgass
Omokuraz 3	60	40		429.78	7.133	0	bgass
Omokuraz 4	60	40		429.78	7.133	0	bgass
Tis Abay I Unit I	11.4	11	16.9	–	2.0512	0	hydro
Wonji	30	16		429.78	7.133	0	bgass
AlutoLangano I	7.3	5	90	785.25	16.19	0	geothermal
Ashegoda II	–	–	–	–	17.63	0	wind
Beles III	30	20		429.78	7.133	0	bgass
EFW-Addis Ababa	25	25	85.42	468.71	147.56	0	solar
Fincha	31	10		429.78	7.133	0	bgass
Fincha Unit I	33.3	32	54.97	28.375	0.5128	0	hydro
Fincha Unit II	33.3	32	54.97	28.375	0.5128	0	hydro
Fincha Unit III	33.3	32	54.97	28.375	0.5128	0	hydro
Fincha Unit IV	34	32.3	54.97	28.375	0.5128	0	hydro
GERD Unit I	400	354	28.07	8.625	0.435	0	hydro
GERD Unit II	400	354	28.07	8.625	0.435	0	hydro
GERD Unit III	400	354	28.07	8.625	0.435	0	hydro

GERD Unit IV	400	354	28.07	8.625	0.435	0	hydro
GERD Unit V	400	354	28.07	8.625	0.435	0	hydro
GERD Unit VI	400	354	28.07	8.625	0.435	0	hydro
GERD Unit VII	400	354	28.07	8.625	0.435	0	hydro
GERD Unit VIII	400	354	28.07	8.625	0.435	0	hydro
GERD Unit VX	400	354	28.07	8.625	0.435	0	hydro
GERD Unit X	400	354	28.07	8.625	0.435	0	hydro
GERD Unit XI	400	354	28.07	8.625	0.435	0	hydro
GERD Unit XII	400	354	28.07	8.625	0.435	0	hydro
GERD Unit XIII	400	354	28.07	8.625	0.435	0	hydro
GERD Unit XIV	400	354	28.07	8.625	0.435	0	hydro
GERD Unit XV	375	351.25	28.07	8.625	0.435	0	hydro
GERD Unit XVI	375	351.25	28.07	8.625	0.435	0	hydro
Gilgel Gibe II Unit I	107	107	55.33	29.99	0.9075	0	hydro
Gilgel Gibe II Unit II	107	107	55.33	29.99	0.9075	0	hydro
Gilgel Gibe II Unit III	107	107	55.33	29.99	0.9075	0	hydro
Gilgel Gibe II Unit IV	107	107	55.33	29.99	0.9075	0	hydro
Gilgel Gibe III Unit I	187	106.7	32.77	15.8	0.569	0	hydro
Gilgel Gibe III Unit II	187	106.7	32.77	15.8	0.569	0	hydro
Gilgel Gibe III Unit III	187	106.7	32.77	15.8	0.569	0	hydro
Gilgel Gibe III Unit IV	187	106.7	32.77	15.8	0.569	0	hydro
Gilgel Gibe III Unit V	187	106.7	32.77	15.8	0.569	0	hydro
Gilgel Gibe III Unit VI	187	106.7	32.77	15.8	0.569	0	hydro
Gilgel Gibe III Unit VII	187	106.7	32.77	15.8	0.569	0	hydro
Gilgel Gibe III Unit VIII	187	106.7	32.77	15.8	0.569	0	hydro

Gilgel Gibe III Unit VX	187	106.7	32.77	15.8	0.569	0	hydro
Gilgel Gibe III Unit X	187	106.7	32.77	15.8	0.569	0	hydro
Kesem	26	16		429.78	7.133	0	bagasse
Melkawakena Unit I	38	38	41.56	35.4675	0.5128	0	hydro
Melkawakena Unit II	38	38	41.56	35.4675	0.5128	0	hydro
Melkawakena Unit III	38	38	41.56	35.4675	0.5128	0	hydro
Melkawakena Unit IV	38	38	41.56	35.4675	0.5128	0	hydro
metehara	100	100	30	468.71	147.56	0	solar
Omokuraz 2	60	40		429.78	7.133	0	bagasse
Omokuraz 5	60	40		429.78	7.133	0	bagasse
Sor I Unit I	2.5	2.5	68.3	–	1.0256	0	hydro
Sor I Unit II	2.5	2.5	68.3	–	1.0256	0	hydro
Tana beles Unit I	115	111	68.35	24.83	1.175	0	hydro
Tana beles Unit II	115	111	68.35	24.83	1.175	0	hydro
Tana beles Unit III	115	111	68.35	24.83	1.175	0	hydro
Tana beles Unit IV	115	111	68.35	24.83	1.175	0	hydro
Tekeze Unit I	75	74.25	53.41	27.21	1.4825	0	hydro
Tekeze Unit II	75	74.25	53.41	27.21	1.4825	0	hydro
Tekeze Unit III	75	74.25	53.41	27.21	1.4825	0	hydro
Tekeze Unit IV	75	74.25	53.41	27.21	1.4825	0	hydro
Tendaho	120	70	80	429.78	7.133	0	geothermal
Tis Abay II Unit I	36.8	34	16.9	112.6	1.0256	0	hydro
Tis Abay II Unit II	36.8	34	16.9	112.6	1.0256	0	hydro
Wolkayit	133	82		429.78	7.133	0	bagasse

Ethiopian power-grid transmission data

COUNTRY CODE	CNTRY_ NAME	VOLTAGE_ KV	FROM_ NM	TO_ NM
ETH	ETHIOPIA	132	ADAMITULU	BUTAJIRA
ETH	ETHIOPIA	230	ADDISABABA	ROBI
ETH	ETHIOPIA	66	ADDISABABA	FICHE
ETH	ETHIOPIA	45	ADDISABABA	DEBREZEYT

ETH	ETHIOPIA	45	ADDISABABA	ADDISALEM
ETH	ETHIOPIA	66	ADDISABABA	WELISO
ETH	ETHIOPIA	132	ADDISABABA	KOMBOLCHA
ETH	ETHIOPIA	132	ADDISABABA	HOLOTA
ETH	ETHIOPIA	45	ADDISABABA	GEJADERA
ETH	ETHIOPIA	66	ADWA	ENDASILASIE
ETH	ETHIOPIA	66	ALAMATA	MAYCHEW
ETH	ETHIOPIA	66	ALAMATA	LALIBELA
ETH	ETHIOPIA	66	ALAMATA	SEKOTA
ETH	ETHIOPIA	230	ALAMATA	MEKELE
ETH	ETHIOPIA	230	ALAMATA	BAHIRDAR
ETH	ETHIOPIA	66	ASBETEFERI	BEDESA
ETH	ETHIOPIA	132	ASELA	KOKA
ETH	ETHIOPIA	66	AWASH	AMIBARA
ETH	ETHIOPIA	230	AWASH	DIREDAWA
ETH	ETHIOPIA	66	AWASH	ASBETEFERI
ETH	ETHIOPIA	132	AWASH	DIREDAWA
ETH	ETHIOPIA	66	BAHIRDAR	GONDER
ETH	ETHIOPIA	132	BAHIRDAR	TIS ABAY
ETH	ETHIOPIA	66	BAHIRDAR	PAWE
ETH	ETHIOPIA	132	BEDELE	METU
ETH	ETHIOPIA	132	BEDELE	NEKEMTE
ETH	ETHIOPIA	132	BONGA	MIZAN
ETH	ETHIOPIA	230	CHEMOGAYEDA	DEBREMARKOS
ETH	ETHIOPIA	66	DEBREMARKOS	FINOTESELAM
ETH	ETHIOPIA	230	DEBREMARKOS	BAHIRDAR
ETH	ETHIOPIA	66	DEBREMARKOS	BICHENA
ETH	ETHIOPIA	132	DILA	MEGA
ETH	ETHIOPIA	66	DIREDAWA	HARER
ETH	ETHIOPIA	66	DIREDAWA	HARER
ETH	ETHIOPIA	132	DIREDAWA	HARER
ETH	ETHIOPIA	230	DIRE DAWA	PK-12
ETH	ETHIOPIA	230	ENDASILASIE	HUMERA
ETH	ETHIOPIA	230	FINCHAA	DEBREMARKOS
ETH	ETHIOPIA	66	GAMBELLA	DEMBIDOLO
ETH	ETHIOPIA	132	GEDO	NEKEMTE
ETH	ETHIOPIA	230	GEDO	ADDISABABA
ETH	ETHIOPIA	66	GEDO	GUDER
ETH	ETHIOPIA	230	GEDO	FINCHAA
ETH	ETHIOPIA	400	GILGEL GIBE	HALELIE-
ETH	ETHIOPIA	132	GILGEL GIBE	HOSAINA

ETH	ETHIOPIA	230	GILGEL GIBE	ADDISABABA
ETH	ETHIOPIA	230	GILGEL GIBE	GEDO
ETH	ETHIOPIA	132	GIMBI	MENDI
ETH	ETHIOPIA	66	GONDER	DABAT

Candidate PP	Capacity (MW$_e$)	Capacity factor	LCOE ($/kWh)	Type	Location	Specifics/inputs
Melka Sedi	137	0.9		biomass	Amibara	Mesquite
Bameza	120	0.25	0.114	biomass	Guba,	wood
Wabi	100–150			hydro	Wabe River	feasibility study
Beko Abo	935	0.81	0.026	hydro	Blue Nile River	live storage: 1.2 km^3
Genji	216	0.49	0.029	hydro	Baro River	diversion weir
Upper Mendaya	1,700	0.57	0.038	hydro	Blue Nile River	live storage: 10.3 km^3
Karadobi	1,600	0.56	0.044	hydro	Blue Nile River	live storage: 18.7 km^3
Geba I+II	385	0.55	0.045	hydro	Geba River	live storage: 1.7 km^3
Sor II	5	0.92	0.058	hydro	Sor River	live storage: 0.3 km^3
Upper Dabus I+II	798	0.51	0.058	hydro	Dabus River	live storage: 2.6 km^3
Tendaho II-IV	555	0.90	0.059	geothermal	Dubti	T >240°Csteam
Aluto III+IV	160	0.90	0.059	geothermal	Aluto	T >240°Csteam
Birbir I+II	564	0.70	0.059	hydro	Birbir River	Live storage: 2.5 km^3
Corbetti II-III	500	0.90	0.059	geothermal	Shashamane	T >210°Csteam
Halele Werabesa	424	0.54	0.061	hydro	River Gibe	live storage: 5.7 km^3
Chemoga Yeda I+II	280	0.45	0.067	hydro	Debre Markos	live storage: 0.5 km^3
Genale Dawa V	146	0.66	0.067	hydro	River Genale	live storage: 0.1 km^3
Abaya	790	0.90	0.071	geothermal	Bilate River	T >210°Csteam
Boseti	265	0.90	0.072	geothermal	near Kone	T >210°Csteam
TAMS	1,700	0.39	0.073	hydro	Baro River	live storage: 4.8 km^3
Meteka	130	0.90	0.073	geothermal	Meteka	T >210°Csteam
Dofan	86	0.90	0.078	geothermal	Dulecha	T >210°Csteam
Baro I+II	645	0.46	0.083	hydro	Baro River	live storage: 1.0 km^3
Lower Didessa	550	0.20	0.083	hydro	Didessa River	live storage: 3.5 km^3

Tekeze II	450	0.69	0.084	hydro	Tekeze River	live storage: 6.6 km^3
Ayisha III-IV	300	0.34	0.09	wind	Ayisha	
Iteya	600	0.32	0.09	wind	Iteya	Assela and Tulu Moye
Mega Maji	100	0.34	0.095	wind	Mega	
Debre Berhan	200	0.3	0.095	wind	Debre Berhan	
Sululta	100	0.26	0.095	wind	Sululta	
Dila	100	0.3	0.1	wind	Dila	
Assela	100	0.28	0.1	wind	Assela	Iteya & Tulu Moye
Tulu Moye II-IV	470	0.90	0.104	geothermal	Arsi Zone	T ≥170°Csteam
Teo	9	0.90	0.104	geothermal	Afar Zone 3	T >210°Csteam
Fantale	120	0.90	0.105	geothermal	Mount Fentale	T ≥170°Csteam
Dallol	44	0.90	0.108	geothermal	Dallol volcano	T >210°Csteam
Dama Ali	230	0.90	0.108	geothermal	Mount Dama Ali	T ≥170°Csteam
Calub	420	0.88	0.109	CCGT	Calub	natural gas
Nazareth	33	0.90	0.109	geothermal	Adama	T ≥170°Csteam
Boina	100	0.90	0.111	geothermal	Alamata	T ≥170°Csteam
Mek'ele	100	0.2	0.12	solar	Mek'ele	
Humera	100	0.2	0.12	solar	Humera	
Gad	125	0.2	0.12	solar	Gad	Solar Phase I
Hurso	125	0.2	0.12	solar	Hurso	Solar Phase II
Dicheto	125	0.2	0.12	solar	NW of Galafi	Solar Phase I
Metema	125	0.2	0.12	solar	Metemma	Solar Phase II
Weranso	150	0.2	0.12	solar	Weranso	
Welenchiti	150	0.2	0.12	solar	Welenchiti	
Gojeb	150	0.48	0.127	hydro	Gojeb River	live storage: 1.0 km^3
Aleltu East	189	0.53	0.128	hydro	Aleltu River	live storage: 0.6 km^3
Aleltu West	265	0.46	0.149	hydro	Aleltu River	live storage: 0.6 km^3
Wabi Shebele	88	0.91	0.161	hydro	Shebelle River	live storage: 3.3 km^3
Lower Dabus	250	0.29	0.177	hydro	Dabus River	live storage: 1.4 km^3
Total planned	18,617					
Total ≤0.11 \$/kWh	15,201					
Total ≤0.08 \$/kWh	11,257					