



# Security Constrained Economic Dispatch of Renewable Energy Systems

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**Abstract.** This paper presents 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 provide secure and reliable service. Each of these sources requires problem formulation and constraint handling mechanism that take into account security limits and credible contingencies. Modified IEEE 118 bus system (NREL-118 test system), Ethiopian renewable energy system, and modified New England 39-bus system with high RES penetration features were used as case studies. Modeling and simulation was conducted on MATLAB, MATLAB/MATPOER, and DIGSILENT power factory simulation platforms. According to the simulation results obtained, it is deduced that the economic dispatch of RES is a promising step in connection to developments needed in the adoption and realization of smarter grids.

**Keywords:** Security constraints · Economic dispatch · Power system operation · Integrated Renewable energy sources

## 1 Introduction

When a sudden interruption or blackout occurs, we notice the importance of electricity in our daily lives. Moreover, a sudden and uncontrolled power outage can cause a highly regarded threat to social and economic endeavors of energy-addicted society. Considering the Ethiopian electric power network, a power-system of integrated renewable energy sources, the supply of power interrupts every time it rains. These interruptions can impose considerable damage to production plants, service centers, and home appliances [1].

Blackout report data of Ethiopian electric power network (2013–2016), reported 15 major blackouts. 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 [1, 2]. 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 reliable supply of power, it is therefore essential to maintain the balance between generation and demand.

This aspect requires a method of balancing generation and demand considering generation limits, transmission security constraints, contingencies, and uncertainties i.e. Security-constrained economic dispatch (SCED). SCED is allocating generation levels to the generating units in a power system so that the system load can be supplied entirely and most economically while satisfying different security constraints [3, 4]. In the energy market context, the main objective of SCED is to minimize the operation cost while continuously respecting the operational constraints of the power system network. This means minimizing the cost function subject to generation limits, transmission constraints, and security level limits.

Several authors used different methods to solve this problem, for example, iterative method, gradient-based techniques, interior point method, linear programming and dynamic programming [5]. A substantial number of articles reported SCED in the perspective of artificial intelligence [6], integrated renewable energy source [7, 8], and post-disturbance corrective actions [9]. Stephen Frank et al. [10, 11] examines the recent trends towards stochastic, or non-deterministic, search techniques and hybrid methods for OPF.

The other challenging aspect is the intermittency and variability of renewable energy sources. With increasing emphasis on using renewables to mitigate climate change effects, many new challenges hinder the power industry from advancement [12]. A small change in a variable renewable source can cause a large surplus or lack of power output and subsequently affect the security of power system networks with a limited flexibility.

In this paper, it has been put the choice firmly on:

- Reformulating SCED problem including security constraints and credible contingencies.
- Identifying challenges posed to SCED due to intermittent RES penetration.
- Recommending a hybrid computational intelligence-based optimization method for SCED of RES.

Articulation of challenging aspects of economic dispatch with security constraints and uncertainty of renewable energy systems, identification of further challenging developments needed in the adoption of smarter grids, and indicating ways to address them is also the novelty of this study.

**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  
 $C_i$  = constant coefficient of salary and wages  
 $f(x)$  = function to be minimized  
 $FB_{th}$  = biomass generation cost  
 $FG_{th}$  = Geothermal power generation cost  
 $fp_w$  = wind power probability function  
 $F_{sth}$  = solar thermal power generation cost  
 $F_{th}$  = thermal power generation cost  
 $g_l(x)$  = Inequality constraints  
 $G$  = solar irradiance  
 $G_{std}$  = standard solar irradiance  
 $h_k(x)$  = 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  
 $NG$  = Number of generating units  
 $NL$  = Number of security levels  
 $N_{poz}$  = Number of prohibited zones  
 $\phi$  = Credible contingencies  
 $Ph_r$  = Hydropower output  
 $PB_{th}$  = biomass power output  
 $PD$  = Power demand

$C_s$  = solar power generation cost  
 $C_{sp}$  = solar power penalty cost  
 $C_{sr}$  = solar power reserve cost  
 $C_w$  = wind power generation cost  
 $C_{wp}$  = wind power penalty cost  
 $C_{wr}$  = wind power reserve cost  
 $DR I$  = ramp rate limit  
 $PG_{th}$  = geothermal power output  
 $Ph_{gi}$  = Hydropower unit output  
 $P_i \max$  = maximum power generation limit  
 $P_i \min$  = minimum power generation limit  
 $PL$  = 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/m<sup>2</sup>  
 $SI$  = Security level  
 $SI \max$  = 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

**2 Renewable Energy Systems**

The contribution of renewable resources to the energy portfolio globally has been steadily increasing over the past few years [4]. RES 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 [9]. 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 environment of communities [13, 14] (Fig. 1).

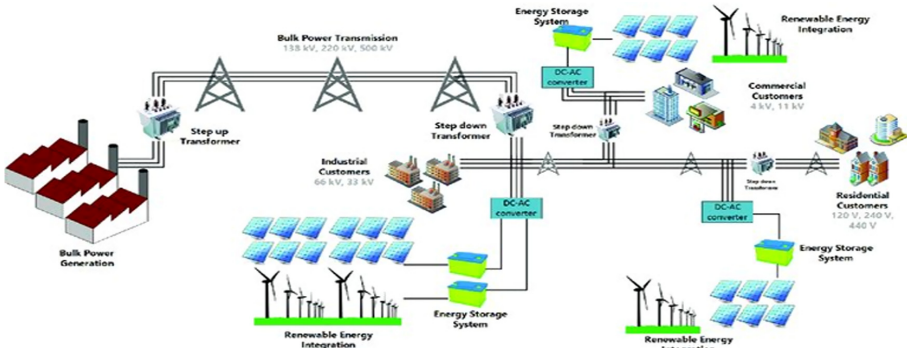


Fig. 1. Possible schematic diagram of RES [11]

Several number of renewable integration studies have focused on optimization requirements of power system with high renewable penetration such as wind [7, 15] gas [12] natural gas [16] and photovoltaic (PV) [17]. In this seminar paper RES 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.

### 3 SCED Problem Formulation

#### 3.1 Problem Formulation

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 [18, 19]. The general form of SCED problem is:

$$\text{optimize } f(x), x \in R^n \tag{1}$$

Subject to

$$h_k(x) = 0 \forall 1, 2 \dots m \tag{2}$$

$$g_l(x) \leq 0 \forall 1, 2 \dots L \tag{3}$$

In a practical power system, the SCED problem is non-linear and multi-objective due to operation constraints. The non-detailed formulation of SCED problem due to the

necessary assumptions can lead to a limitation in the modelling of a large-scale power system. General form of multi objective optimization is:

$$\text{Optimize } f(x) = (f_1(x), f_2(x), f_{Nobj}(x)) \quad (4)$$

Subject to

$$g_l(x) = 0 \forall i = 1, 2, \dots, m$$

$$h_k(x) \leq 0 \forall k = 1, 2, \dots, K$$

$$x_i(1) \leq x_i \leq x_i(0) \quad (5)$$

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 and intermittent generation [9]. 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. This paper uses renewable resources as inputs to RES such as biomass, hydro, solar, wind, and geothermal. Each of these sources requires problem formulation, and constraint handling mechanisms.

Hydro:  $f_1(x)$  represents objective function of hydro power generation plants [20]

$$\min f_1(x) = C_h \sum_{i=1}^{N_{hg}} P_{hgj}(t) \quad (6)$$

Where

$$P_{hgj}(t) = \sum_{t=1}^{24} \sum_{i=1}^{N_G} 0.00981 \eta_i H_{ij} Q_{ij} \quad (7)$$

Wind: the power for assumed wind speed is given by [7, 21]:

$$P_{wr} = \begin{cases} 0, \text{ for } v_{wt} \leq v_i \text{ and } v_{out} \geq 0 \\ P_{wr} \left( \frac{v_{wt} - v_i}{v_r - v_i} \right), \text{ for } v_i \leq v_{wr} \leq v_{out} \\ P_{wr}, \text{ for } v_r \leq v_{wt} \leq v_{out} \end{cases} \quad (8)$$

In addition, its corresponding objective function is  $f_2(x)$

$$f_2(x) = C_w \sum_{i=1}^{N_{WG}} P_{wgj}(t) + \sum_{t=1}^{24} \sum_{i=1}^{N_{WG}} C_R + C_P \quad (9)$$

$C_R$  and  $C_P$  defined by  $C_{Rw} + P_{wj}(t) - (P_{wrj}(t) - \alpha V)$ ,  $C_{Pw} + ((P_{wj}(t) - \alpha V) - P_{wrj}(t))$  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 [8, 21]. 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:

$$f_{pw} = \frac{Krv_i}{P_{wc}} \left[ \frac{1 + \frac{hp_w(v_r)}{P_{wr}}}{C} \right]^{K-1} x e^{\left[ \frac{hp_w(v_r)}{P_{wr}} \right]_K} \tag{10}$$

Where K and C are Weibull probability distribution factors.

$$K = \left( \frac{\sigma}{v_m} \right)^{-1.086} \tag{11}$$

$$C = \frac{V_m}{T(1 + \frac{1}{K})} \tag{12}$$

Solar PV: the solar power output that can be extracted from a given solar irradiance G is [14, 22]:

$$P_{sgj}(t) = P_{sg}(G) = P_{srj} \left( \frac{G^2}{G_{std} + R_{ca}} \right) \tag{13}$$

And its corresponding objective function is represented by  $f_3(x)$

$$f_3(x) = C_s \sum_{i=1}^{N_{sg}} P_{sgj}(t) + \sum_{t=1}^{24} \sum_{i=1}^{N_{sg}} C_R + C_P \tag{14}$$

Where for  $0 < G < R$  ca:

$$P_{sgj}(t) = \sum_{t=1}^{24} \sum_{i=1}^{N_{sg}} (C_R + C_P) \tag{15}$$

$C_R$  and  $C_P$  defined by  $C_{RS} + P_{Sj}(t) - (P_{Srj}(t) - \alpha V)$ ,  $C_{PS} + ((P_{Sj}(t) - \alpha V) - P_{Srj}(t))$  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 Weibull probability distribution function [23, 24].

Thermal: Despite the difference in their constraints, renewable energy sources adapted from thermal power plants have similar objective function [24, 25]. REs adapted from thermal power plant considered in this study include geothermal power plants, solar thermal power plants, biomass and waste to energy plants.

$$f_4(x) = C_{th} \sum_{i=1}^{N_{th}} P_{thj}(t) \left[ \alpha_1 \sum_{i=1}^{N_{Gth}} F_{Gth} P_{Gth} + \alpha_2 \sum_{i=1}^{N_{Sth}} F_{Sth} P_{Sth} + \alpha_3 \sum_{i=1}^{N_{Bth}} F_{Bth} P_{Bth} \right] \tag{16}$$

Where

$$F_{th} = a_i P_{th}^2 + b_i P_{th} + c_i \tag{17}$$

$$F_{Gth} = a_i P_{Gth}^2 + b_i P_{Gth} + c_i \quad (18)$$

$$F_{Sth} = a_i P_{Sth}^2 + b_i P_{Sth} + c_i \quad (19)$$

$$F_{Bth} = a_i P_{Bth}^2 + b_i P_{Bth} + c_i \quad (20)$$

### 3.2 Constraint Formulation

In power systems, continuously respected operation constraints and limits ensure a reliable and secure operation of the system.

#### 1. Demand and generation balance

$$P_D + P_L = \sum_{i=1}^{N_{hgg}} P_{hg} + \sum_{i=1}^{N_{wg}} P_{wg} + \sum_{i=1}^{N_{sg}} P_{sg} + \sum_{i=1}^{N_{th}} P_{th} \quad (21)$$

#### 2. Generation limits

$$P_i^{\min} \leq P_i \leq P_i^{\max} \quad (22)$$

$$P_{\min} \leq 0.00981 \eta_i H_{ij} Q_{ij} \leq P_{\max} \quad (23)$$

$$0 \leq P_{wj}(t) \leq P_{wr} \quad (24)$$

$$0 \leq P_{sj}(t) \leq P_{sr} \quad (25)$$

$$0 \leq P_{hj}(t) \leq P_{hr} \quad (26)$$

#### 3. Prohibited operating zones

$$P_i^{\min} \leq P_i \leq P_i^{Lj} \quad \forall j = 1, 2, \dots, N_{Poz} \quad (27)$$

$$P_i^{Vj-1} \leq P_i \leq P_i^{lj} \quad (28)$$

$$P_i^{Vj-1} \leq P_i \leq P_i^{\max} \quad (29)$$

#### 4. Transmission constraints: For transmission constraints Kron's loss equation is considered

$$P_L = \sum_{i=1}^n \sum_{j=1}^m P_{gi} B_{ij} P_{gj} = B_{oo} + \sum_{i=1}^n B_{io} P_{gi} + \sum_{i=1}^n \sum_{j=1}^m P_{gi} B_{ij} P_{gj} \quad (30)$$

Where

$$B_{ij} = \frac{\cos(\theta_i - \theta_j)R_{ij}}{\cos \phi_i \cos \phi_j V_i V_j} \tag{31}$$

$$B_{oo} = \sum_{i=1}^n \sum_{j=1}^m P_{Di} B_{ij} P_{Dj} \tag{32}$$

$$B_{ij} = - \sum_{j=1}^m (B_{ij} + B_{ji}) \tag{33}$$

5. Security limits

$$S_1 \leq S_1^{\max} \forall l = 1, 2 \dots N_L \tag{34}$$

$$\phi_j P(t) > o \forall j = 1, 2 \dots N_C \tag{35}$$

6. Generator ramp rate limits

$$\max(P_i^{\min}, P_i^{t-1} - DR_i) \leq P_i(t) \leq \min(P_i^{\max}, P_i^{t-1} + DR_i) \tag{36}$$

7. Spinning reserve limits

$$\sum_{i=1}^{N_G} S_{Ri} \geq S_{Sr} \tag{37}$$

8. Water discharge and reservoir limits:

$$X_i^{\min} \leq X_i \leq X_i^{\max} \tag{38}$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \tag{39}$$

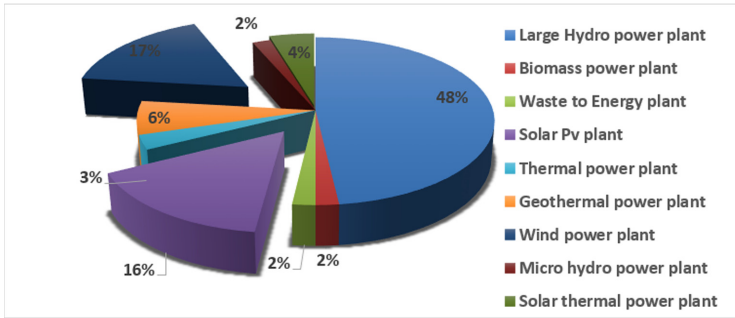
$$Q_i^{\min} \leq Q_{ij} \leq Q_j^{\max} \tag{40}$$

$$V_i^{\min} \leq V_{ij} \leq V_j^{\max} \tag{41}$$

$$V_{i,j+1} = V_{ij} - (Q_{ij} - q_i + S_{ij})\Delta t + \sum_{K \in K_j} (Q_{ij} + S_{kij} + I_j)\Delta t \tag{42}$$

9. Renewable energy penetration rate constraints

$$P_{wj}(t) + P_{sj}(t) + P_{hj}(t) + P_{thj}(t) \leq \Psi P_D \tag{43}$$



**Fig. 2.** Considered energy share of RES adopted from modified IEEE 118 bus system zone 2&3

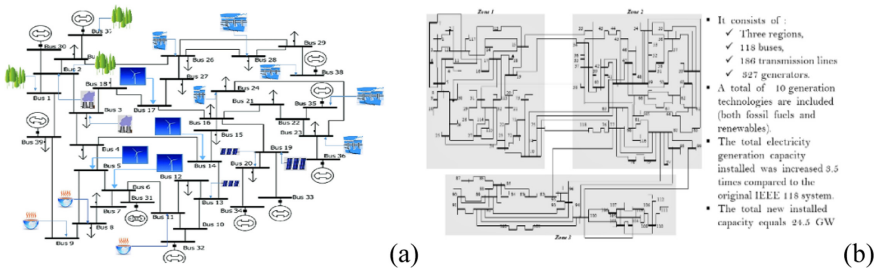
Constraint (9) considers thermal (biomass, solar-thermal, geothermal), hydro, wind, and solar PV penetration ratios,  $\psi$ . And their energy share adopted from Ethiopian energy system according to editing and adopting features of NREL IEEE 118 bus system zones is given in the figure below [13, 26] (Fig. 2).

Hasnae Bilil et al. [27] formulated a multi-objective problem that allows optimization of both the annualized renewable energy cost and the system reliability defined as the renewable energy load disparity (RELD) considering the lack of energy as well as the exceed weighted by a penalty factor. The instability created by the integration of variable renewable energy sources made SCED a complex optimization problem [28]. Regarding wind energy penetration, several methods have been used to solve this problem [29]. Stephen Frank et al. [11] generally gives state of the art, recent developments and future trends of power flow and examines the recent trend towards stochastic, or non-deterministic, search techniques and hybrid methods for OPF.

## 4 Case Studies and Solution Methods

Many researchers use case study/test system databases for a number of important areas of power systems operations and planning, including unit commitment, economic dispatch, optimized allocation of distributed generation, fault detection [26]. However, there are a number of fundamental limitations associated with many current test systems, such as considering only very brief periods, having generally smaller systems than those seen in practice, and other aspects that make many practitioners view them as unrealistic [26]. For this limitations research facilities are intensively improving, updating and deploying state of the art test systems including modified IEEE 118 bus system and modified New England 39 Bus system (Fig. 3, Table 1).

NREL-118 test system, using the transmission representation of the IEEE 118-bus test system best suits for high penetration of renewable energy sources. NREL-118 system includes information, which is currently not included in other public IEEE bus test systems. These are detailed generation constraints (upward/downward ramping, minimum generation level, minimum up/down times, heat rate and fuel use at different load levels, start and shutdown costs) and time-synchronous yearlong actual and day-ahead forecast time series for wind and solar power as well as regional electricity load [26].



**Fig. 3.** (a) Modified New England 39 Bus system [13] (b). NREL-118test system [26]

**Table 1.** Data sources and usage

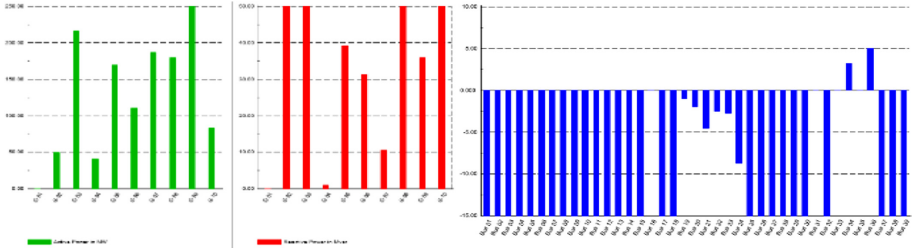
| Test system                                    | Data source  | Ref  | Details   |
|--|--|------|---|
| Modified New England 39-Bus System             | <ul style="list-style-type: none"> <li>• Illinois center for a smarter electric grid(ICSEG),</li> <li>• Dynamic IEEE test systems,</li> <li>• Eelectric grid test repository,</li> </ul>               | [13] | <ul style="list-style-type: none"> <li>• <a href="https://icseg.iti.illinois.edu/ieee-39-bus-system/">https://icseg.iti.illinois.edu/ieee-39-bus-system/</a>,</li> <li>• <a href="https://www.kios.ucy.ac.cy/testsystems/index.php/dynamic-ieee-test-systems/ieee-39-bus-modified-test-system">https://www.kios.ucy.ac.cy/testsystems/index.php/dynamic-ieee-test-systems/ieee-39-bus-modified-test-system</a>,</li> <li>• <a href="https://electricgrids.engr.tamu.edu/electric-grid-test-cases/new-england-ieee-39-bus-system/">https://electricgrids.engr.tamu.edu/electric-grid-test-cases/new-england-ieee-39-bus-system/</a></li> </ul> |
| NREL IEEE-118 bus system                       | <ul style="list-style-type: none"> <li>• NREL: transforming energy</li> <li>• Electric grid test repository</li> <li>• U.S. Department of Energy Office of Scientific Technical Information</li> </ul> | [26] | <ul style="list-style-type: none"> <li>• <a href="https://www.nrel.gov/news/program/2016/21643.html">https://www.nrel.gov/news/program/2016/21643.html</a></li> <li>• <a href="https://electricgrids.engr.tamu.edu/electric-grid-test-cases/ieee-118-bus-system/">https://electricgrids.engr.tamu.edu/electric-grid-test-cases/ieee-118-bus-system/</a></li> <li>• <a href="https://www.osti.gov/biblio/1416258-extended-ieee-bus-test-system-high-renewable-penetration">https://www.osti.gov/biblio/1416258-extended-ieee-bus-test-system-high-renewable-penetration</a></li> </ul>   |
| Ethiopian renewable energy system <sup>1</sup> | <ul style="list-style-type: none"> <li>• Energypedia</li> <li>• Export gov</li> </ul>  | [1]  | <ul style="list-style-type: none"> <li>• <a href="https://energypedia.info/wiki/Ethiopia_Energy_Situation">https://energypedia.info/wiki/Ethiopia_Energy_Situation</a></li> <li>• <a href="https://www.export.gov/article?id=Ethiopia-Energy">https://www.export.gov/article?id=Ethiopia-Energy</a></li> </ul>  |

Ethiopian renewable energy system is not a complete test system. It has been adopted in this study so that its economic dispatch can be tested within zones that exhibit full and complete dispatch data set.

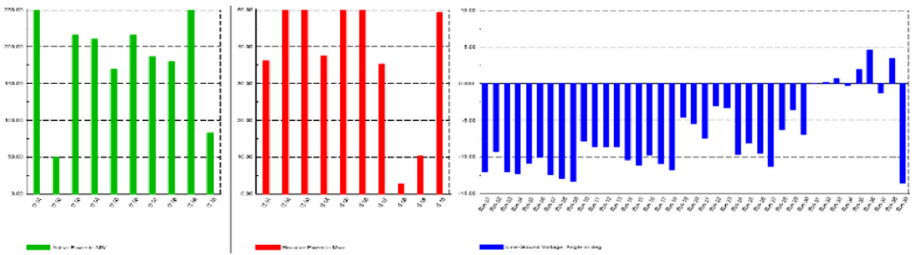
In this study, the modified IEEE 118 bus system modified New England 39 Bus system and Ethiopian renewable energy systems were selected case studies with high renewables penetration features to consider security levels and credible contingencies. The solution method employed to solve this optimization problem emanates from its problem formulation and it is multi-objective multivariable optimization method. DIGSILENT Power factory and MATLAB/MATPOWER 6.0 simulation tools were used.

### 5 Results and Discussions

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

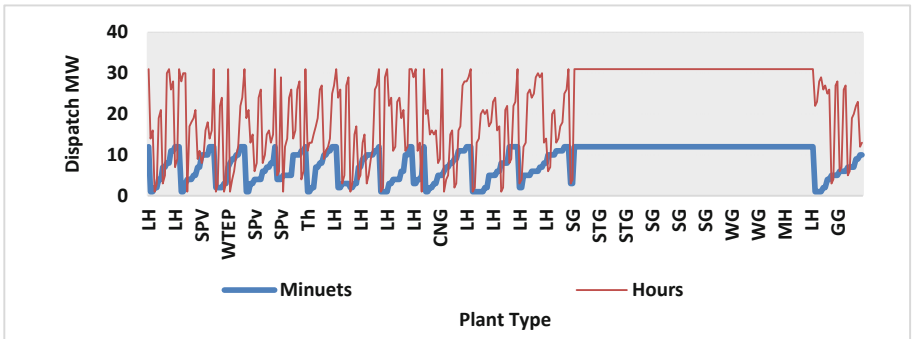


**Fig. 4.** Active and reactive power dispatch, voltage and power angle deviation of New England 39 Bus system with no RES



**Fig. 5.** Active /reactive power dispatch, voltage & power angle deviation of modified New England 39 Bus system with RES

Figures 4 and 5 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



**Fig. 6.** Generation cost in an hourly and minutely basis

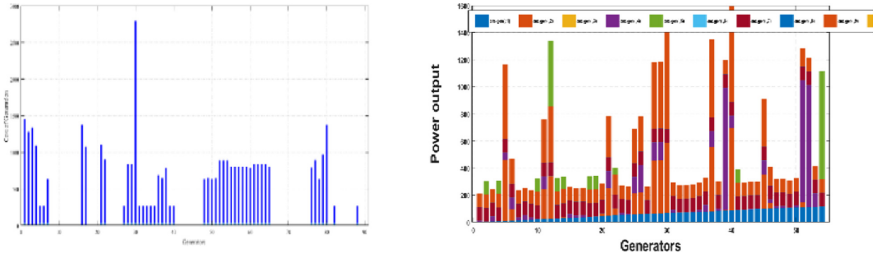


Fig. 7. Power generation dispatch of the involved RES

renewables entry is used. It clearly shows the effect of demand –supply affecting the power angle and voltage. This part of the study is challenging to carry out on MATLAB.

Figures 6 and 7 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.

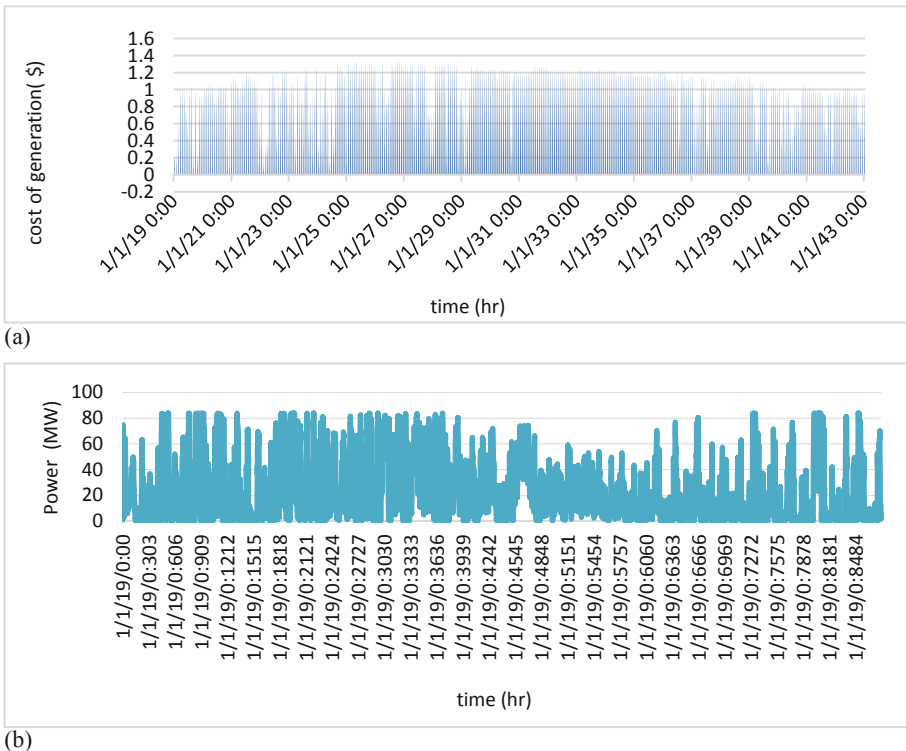
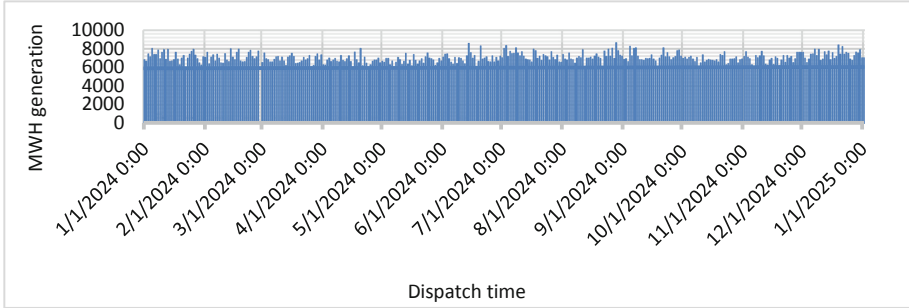


Fig. 8. (a).Generation dispatch of Ethiopian renewables and (b) generation cost of Ethiopian energy systems

Figure 8 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.



**Fig. 9.** Daily MWh generation dispatch

Figure 9 presents the total MWh dispatch of the RESs for NREL 118 bus system.

**Table 2.** Multi-variable multi-objective simulation results

| Gen                  | Plant Type | MVMO solution | Gen | Plan Type            | MVMO solution |
|----------------------|------------|---------------|-----|----------------------|---------------|
|                      | 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                 |            | 1279.17       |     | Cost (\$/hr)         | 1601.26       |
| <b>P<sub>L</sub></b> |            | 14.382        |     | <b>P<sub>L</sub></b> | 19.605        |

Table 2 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 Conclusions

This paper presents Security Constrained Economic Dispatch (SCED) of renewable energy systems (RES). Reformulation of SCED for RES comprising biomass, large and small hydro, solar PV, and solar thermal, waste to energy plant, wind farm, and geothermal was carried out.

Each of these sources requires problem formulation and constraint handling mechanisms that consider credible contingencies. Modified IEEE 118 bus system (NREL-118test system), modified New England 39-Bus system and Ethiopian renewable energy systems with high penetration of RES were used as case studies. Modeling and simulation was conducted on MATLAB/MATPOER, and DIGSILENT power factory simulation platforms.

According to the simulation results, it can be deduced that economic dispatch of RES with their security constraints is a promising step towards the realization of smart and modern grid operation. As part of future work, it is recommend a hybrid computational intelligence based optimization method for SCED of integrated renewable energy sources.

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