sustainability

MDPI

Article

Analysis of System Balancing and Wind Power Curtailment Challenges in the Ethiopian Power System under Different Scenarios

Kena Likassa Nefabas [1,*], Mengesha Mamo [1] and Lennart Söder [2]

[1] School of Electrical and Computer Engineering, AAU Addis Ababa University, Addis Ababa 3614, Ethiopia; mengesha.mamo@aau.edu.et
[2] Department of Electric Power & Energy Systems, KTH Royal Institute of Technology, 10044 Stockholm, Sweden; lsod@kth.se
* Correspondence: kena0912@gmail.com or kena2@kth.se; Tel.: +251-911165802

Abstract: In this paper, an hourly dispatch model was developed to analyze the system balancing and wind power curtailment challenges in the future of the Ethiopian electric power grid system. The developed model was validated using historical data and was used for the analysis of the grid system in 2030 with different scenarios. The model was used to examine the impacts of transmission capacity, regulation reserve requirement, and daily minimum generation of hydropower for irrigation with three cases of wind annual energy share of 14.5%, 17.8%, and 25.2%. Thus, the curtailment was found to be below 0.2%, 1.1%, and 9.8% for each case, respectively. The cost of wind energy increases in proportion to the percentage of curtailment and the increase in transmission line capacity. Reducing the minimum hydropower generation results in smaller wind power curtailment and better generation–consumption balancing.

Keywords: balance; curtailment; hydropower; model; wind

check for updates

Citation: Nefabas, K.L.; Mamo, M.; Söder, L. Analysis of System Balancing and Wind Power Curtailment Challenges in the Ethiopian Power System under Different Scenarios. *Sustainability* **2023**, *15*, 11400. https://doi.org/10.3390/su151411400

Academic Editors: Abbas Rabiee and Seyed Masoud Mohseni-Bonab

Received: 8 June 2023
Revised: 17 June 2023
Accepted: 30 June 2023
Published: 22 July 2023

1. Introduction

In any electric power system, the total generation should always be exactly the same as the total consumption [1]. However, it is naturally a challenge for the power system to keep an exact balance between total generation and consumption, including power system losses [2]. The biggest challenge for many power systems is situations in which there is a sudden and large-scale disconnection from the power plant and a loss of the transmission line [3,4]. Another challenge related to keeping continuous balance occurs when variable renewable energy sources, such as wind and solar, are integrated into the national grid [5,6]. These studies have identified three challenges for balancing—handling continuous balancing; low wind and solar power production and high power consumption; and situations in which there is high wind and solar power production and low power consumption.

The increase in electricity generation from variable renewable energy sources i.e., from wind and solar, makes the balancing of power systems more difficult. One of the difficulties faced by system operators is when there is more power available from variable renewable sources than can be accommodated by the electric power system grid. During these conditions, the extra power can either be exported to neighboring countries or stored, or generation can be reduced to below the available capacity, which is known as curtailment [7].

The system balancing problem might lead to curtailment due to a bottleneck in transmission lines, reserve requirements, the minimum generation requirements of conventional power plants, a limited flexibility of the power system, and the integration level of wind and solar power. However, depending on the characteristics and operation rules of the

power system, the amount of curtailment and the challenges of system balancing vary between different systems.

In Sweden, by 2025 curtailment is estimated to be 0.3% of the available generation for a 26 GW wind scenario and below 1.7% for a 33 GW wind scenario [8]. The reason for curtailment is the limited flexibility of thermal power plants and the reduced capacity of transmission lines due to failures.

In the Ethiopian power system, which is largely based on hydropower (more than 93% of total generation in 2020), operators have so far not needed to worry about the curtailment of wind generation due to an insignificant penetration level. However, the rapid increase in wind power capacity in the country will agitate curtailment in the future. Ethiopian Electric Power has a plan to integrate 1450 MW of solar power and 3844 MW of wind power, in addition to the existing plants, by 2030.

There are many studies that have analyzed the need to curtail renewable power generation in future power systems. The authors of [9] predicted how much wind was to be curtailed in 2020 in the Irish power system. The study identified the impact of the amount of offshore wind on wind curtailment, the allowed limit of system non-synchronous penetration (SNSP), and the inclusion or exclusion of transmission constraints. Another article [10] studied wind power curtailment in China in 2016 and identified around 49.7 TWh of curtailment per year, which is significant.

Task 25 of the International Energy Agency (IEA) Wind Technology Collaboration program [11] led to the finding that high penetrations of wind and solar generation in power systems result in increasing curtailment. The paper discussed how much curtailment is occurring, how it is occurring, why it is occurring, and what is being done to reduce curtailment.

Article [12] assessed how operational flexibility and the curtailment of renewable energy are connected by using a unit commitment and economic dispatch model that included operational characteristics of conventional power plants and system constraints for a power system in Great Britain. The result shows that an increase in curtailment is mostly expected as wind deployment increases. The study found that curtailment reached 17% of the annual available variable renewable electricity generation.

There is a large body of literature related to the balancing of wind power. Article [13] studied how to balance wind power using demand-side management during high penetrations of wind energy. Other studies [14–18] have examined the balancing of wind power using different methods for different countries.

However, there have been no similar studies of the Ethiopian power system. The reason for this is probably that the integrated wind power capacity of Ethiopia is not yet significant. According to the report from the National Electrification Program, in the year 2022 G.C, approximately 40 percent of the population, with a per capita consumption of 143 kWh per year, was connected to the grid despite the large potential of renewable energy resources, particularly wind power [19] (see Table 1). The government of Ethiopia (GoE) has set an ambitious plan for the coming year to increase energy generation, particularly from renewable energy, to boost access to electricity and per capita energy consumption [20]. Thus, an assessment of the expected future balancing challenges and wind power curtailment in the Ethiopian power system is relevant and desirable. This analysis should capture curtailment due to transmission line congestion, limitations in hydro flexibility due to the daily minimum generation for irrigation, and curtailment arising from regulation reserve requirements.

For this purpose, we developed an hourly dispatch model of the Ethiopian power system. The model considers hourly average production values and includes the net transmission line capacity for the neighboring countries. It includes the hourly generation capacities of different types of generation, and uses a cascaded model for hydropower generation. Wind power was modeled based on ERA-5 reanalysis data and information about existing wind farms [21], and solar power production time series were taken from a meteorological model called the system advisory model [22].

In this developed model, wind generation curtailment occurs when other types of generation are at their minimum generation limits, there is no more transmission capacity for exporting the excess wind power, and the reserve requirement is increased. Thus, the model was used to assess the system balancing challenge and the amount of wind curtailment under future power system scenarios, considering the expected changes in wind power, load, hydropower generation, and transmission capacity by 2030.

Table 1. Ethiopia indigenous energy resources [19].

Resource	Unit	Exploitable Reserve	Exploited Percent
Hydropower	GW	45	<5
Wind power	GW	1350	<1
Solar/day	kWh/m^2	5.5	<1
Geothermal	GW	7	<1
Wood	Million tons	1120	50
Agricultural waste	Million tons	15–20	30
Natural gas	Billions m^3	113	0
Coal	Million tons	300	0
Oil shale	Million tons	253	0

In total, 24 different cases were studied in order to investigate the impact of the amount of wind power and different system configurations on curtailment and system balancing. The results show that the most important measures to reduce curtailment and system balancing would be to increase the transmission capacity of certain connections and to reduce the scheduled irrigation if possible, while regulating reserve requirements has less impact.

Thus, this paper contributes the following novelty to the research community. We develop a model to simulate the Ethiopian power system, which has not been done so far, and the developed model can be seen in (Section 3 Model Formulation and Case Study Setup). Furthermore, using the model, we analyze the wind power curtailment and system balancing challenges under future scenarios for the Ethiopian power system, considering transmission capacity, regulation reserve requirements, and the minimum generation of hydropower (generation flexibility), and this can also be seen in (Section 4 Result and Discussion). In addition to this, this paper studies the impacts of operational constraints such as reserve requirement, minimum power generation, and transmission line constraints on system balancing and wind power curtailment challenges.

Thus, the other sections of the paper are summarized as follows: Section 2 deals with the data and model implementation, Section 3 explains the mathematical formulation of the model and the case study setup, Section 4 presents the results and discussions, and finally Section 5 gives a conclusion and considerations for future work.

2. Data and Model Implementation

The model is implemented on the Ethiopian power system considering the net transmission capacity to neighboring countries like Djibouti, Sudan, Kenya, and Tanzania. As of 2020, the net transfer capacity was 100 MW, 200 MW, 0 MW, and 0 MW to Djibouti, Sudan, Kenya, and Tanzania respectively. The implementation of the model is on the Ethiopian power system, and its export considers the full capacity of the transmission line, planned for the year 2030 [19]. As the literature explains, 75% of Sudan's electricity supply mainly comes from fossil fuels [23], which is more expensive compared to the renewable energy in Ethiopia. Therefore, Ethiopia can export more energy to Sudan when surplus production is available. The main parts of the data used for the model to be implemented are described in the subsequent sections as follows:

1. Generation and transmission capacity;
2. Load profile;

3. Reservoir inflow;
4. Wind power production;
5. Solar power production.

We implemented the model in Julia with Gurobi 9.14 to solve the optimization problem. For each scenario, solving the model for a whole year took around 20 min on a computer with Intel Core i7-4790 CPU @ 3.6 GHz and 32 GB of RAM.

2.1. Generation Capacities

The installed capacities of the power plants used in the model were based mainly on data from the Ethiopian Electric Power (EEP) master plan [24]. The master plan provided the total installed capacity and average annual energy production of each generation type. Furthermore, in the master plan, there were potential planned power plants to be included in the national grid for the year 2030. The power plants contained in the master plan are hydro, wind, solar, and thermal.

Table 2 shows all existing and planned hydropower plants for the year 2030 in Ethiopia's power system. The table also shows the name of the hydropower plant, the installed capacity, and the average annual generating capacity of each hydropower plant. The topology of cascaded hydropower plants is also shown in Figure 1.

Table 2. Existing and planned hydro power plants [24]. UC represents plants under construction.

Hydropower Plants	Capacity [MW]	Year of Commission	Status	Average Annual Generating Capacity [MWh]
Koka	43	1960	Existing	133,470
Awash II	32	1966	Existing	183,480
Awash III	32	1971	Existing	184,220
Tisabay I	11	1964/2000	Existing	1700
Tisabay II	67	2001	Existing	10,100
Koisha	2160	2022	Existing	6,460,000
Tana Beles	460	2010	Existing	2,748,740
Fincha	128	1974	Existing	614,670
Genale Dawa III	254	2018	Existing	1,690,560
Gilgel gibe I	210	2004	Existing	882,130
Gilgel gibe II	420	2010	Existing	2,030,170
Gilgel gibe III	1870	2010	Existing	5,348,270
Melkawakena	153	1988/2014	Existing	555,490
Amertineshe	97	2013	Existing	245,000
Tekeze	300	2009	Existing	1,399,480
GERD	5150	2024	UC	14,684,100
Baro I	166	2023	Plan	651,710
Baro II	507	2023	Plan	1,573,186
Birbir	467	2023	Plan	2,716,650
Dabus	304	2023	Plan	2,626,082
Geba I	214	2023	Plan	951,970
Geba II	157	2023	Plan	753,490
Genale V	100	2023	Plan	572,990
Genale VI	246	2023	Plan	1,528,460
Genji	214	2023	Plan	814,100
Halele	96	2024	Plan	449,770
Karadobi	1600	2029	Plan	7,830,780
Tams	1700	2025	Plan	5,714,000
Warabesa	340	2024	Plan	224,885
Yeda I	162	2023	Plan	627,110
Yeda II	118	2023	Plan	460,450
Total				64,667,213

The total installed capacity in 2020 and the total expected capacity in 2030 for each technology is shown in Table 3. From this table, one can also see that the total maximum

annual generation of each hydropower plant is given. These data are the simulation results of many hydrological years obatined from EEP. Therefore, in this model, this annual average inflow is assumed as a maximum yearly energy production. Hydropower is also used for ramping and reserve provision as well. Regarding the ramp rate, it is assumed that hydropower can fully ramp to its installed capacity.

Table 3. Capacity of power plants included in the model from EEP plan [24].

Technology	2020 [MW]	2030 [MW]	Total Annual Energy in 2030 [TWh]
Hydro	4077	17,628	64.67
Wind	324	3844	11.8
Solar	0	1450	3.2
Thermal	32.3	1441	9.37

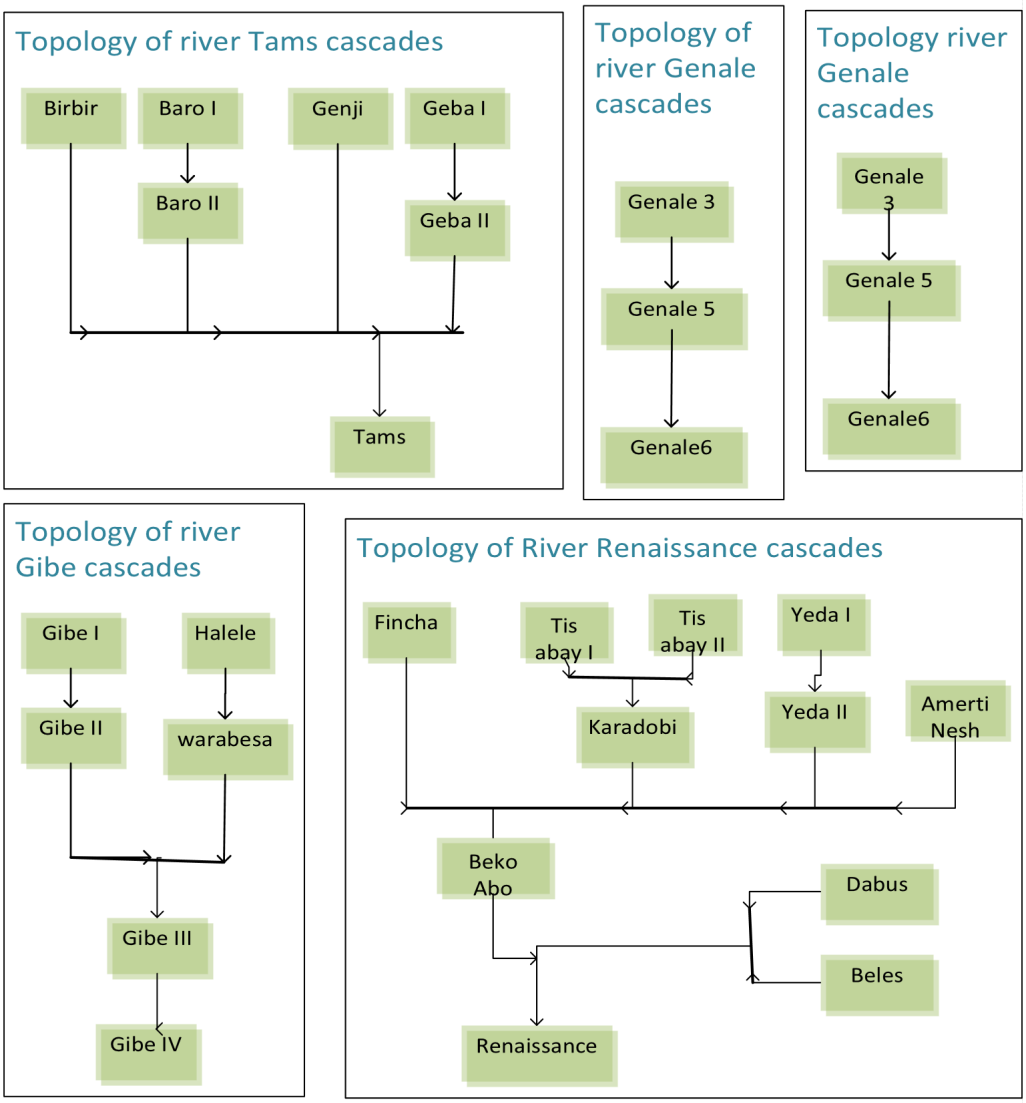

Figure 1. This figure shows the cascaded hydropower plants used in the simulation. The arrow in the figure shows the next reservoir.

2.2. Load Profiles

Hourly load data for the year 2019 have been collected from EEP and business-as-usual methods were applied to scale them up for the year 2030. The formula used for scaling has been shown in Equation (1). The yearly demand in Ethiopia is projected to increase from

16.675 TWh in 2019 to 58.5 TWh in 2030 [24], which corresponds to an annual growth rate of 13.7%. Accordingly, we scaled up the load from 2019 by a factor of 4.25 to represent the load growth from 2019 to 2030. The peak load growth pattern in the country is shown in Figure 2. The figure shows that the peak load growth follows a linear pattern from year to year. The load profile is also shown in Figure 3.

$$Load_{t,2030} = Load_{t,2019} \times \frac{Load_{2030}}{Load_{2019}} \qquad \forall\, t \in \mathcal{T} \tag{1}$$

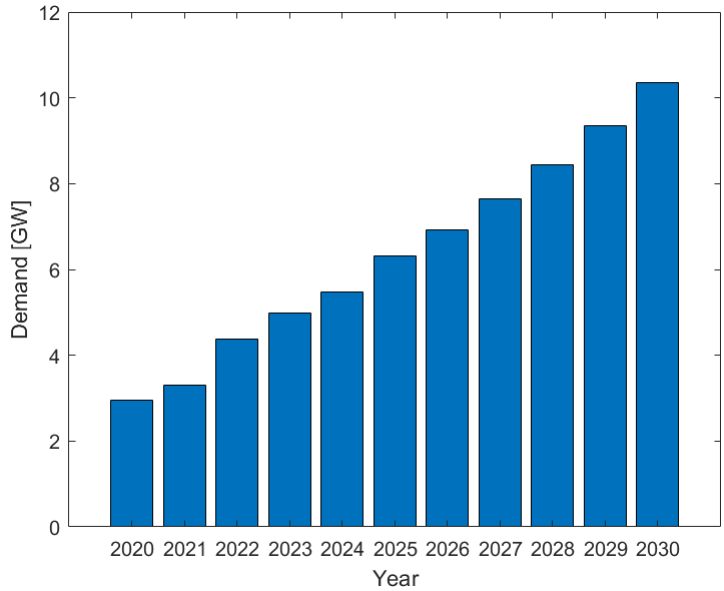

Figure 2. Annual load growth pattern.

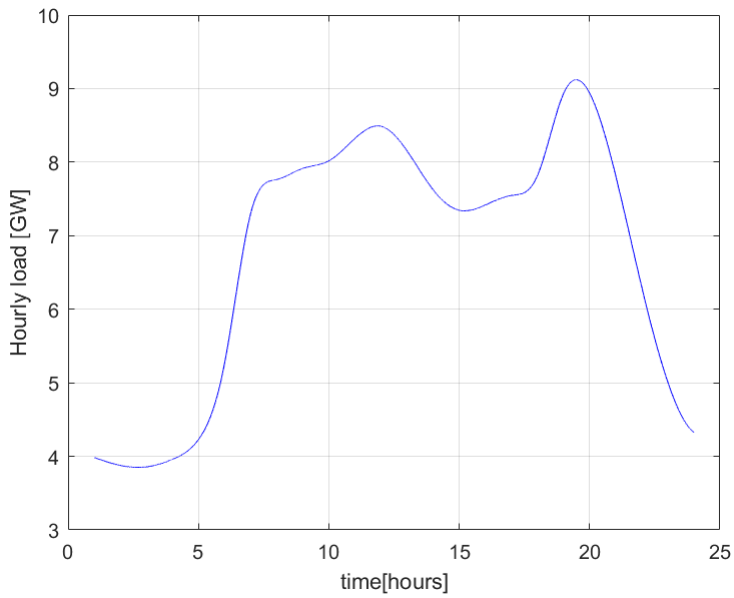

Figure 3. Average daily load profile.

2.3. Wind Power Production

Wind power production time series were created using the model in [21]. The selected wind farms were used to calculate wind production based on ERA5 wind speed data, and the parameters in the model were fit to match the production for historical wind generation. In this way, a realistic wind power production time series could be produced for each

wind farm, using the wind speed data for a given area. Table 4 shows the existing wind power plants.

Table 4. Existing wind power plants [24].

Name of Wind Power Plant	Installed Capacity (MW)	Commissioning Year	Status
AdamaI	51	2011	Existing
Adama II	153	2015	Existing
Ashegoda	120	2010	Existing
Total	324		

2.4. Solar Power Production

In Ethiopia, currently there is no grid-connected solar power, but there is a plan to integrate it in the coming years. Solar power production time series were taken from a meteorological model named system advisory model [22]. The system advisory model (SAM) was developed by the national renewable energy laboratory (NREL). SAM is a free techno-economic software model that facilitates decision making for people in the renewable energy industry.

2.5. Reservoir Inflow

Data for the total reservoir capacity of each hydro resource were obtained from the EEP master plan as mentioned in the previous section. The monthly average reservoir inflow was also obtained from EEP and the data were available for the years 1961–2005. These monthly inflow data were interpolated to obtain hourly inflow. Cubic spline interpolation was applied to obtain more realistic data on the hourly inflow. For example, Figure 4 shows the interpolated inflow of Beles hydropower plant.

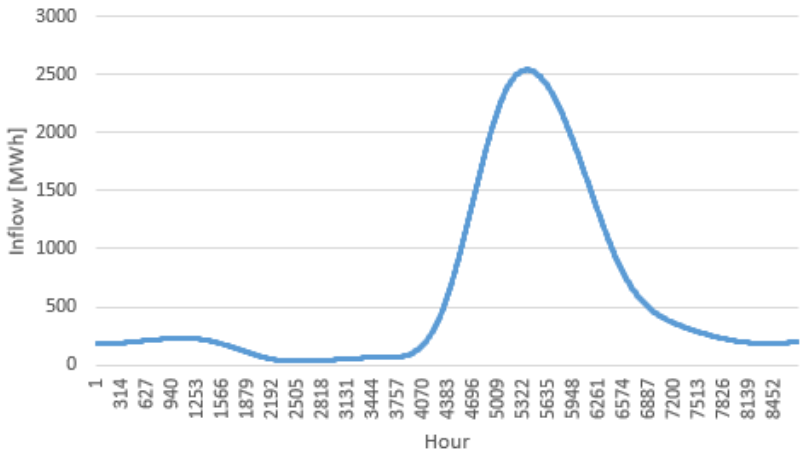

Figure 4. Interpolated inflow for Beles hydropower plants. This is the mean value of 40 years (1965–2005).

3. Model Formulation and Case Study Setup

3.1. Model Formulation

The model was developed for the Ethiopian power system to analyze the wind power curtailment and system balancing challenge for future scenarios. The equations were taken from different sources summarized in [25] and adopted so that they were suitable for the Ethiopian power system.

3.1.1. Objective

The system cost to be minimized is given by

$$\sum_{t\in\mathcal{T}}\left((c_{ns}\times\Lambda_{a,t})+(c_w\times p_{g,a,t})-\sum_{l\in\mathcal{Z}}(c_{exp}\times exp_{l,a,t})\right)\forall g\in wind \tag{2}$$

where the terms in order are the cost of load shedding, the cost of wind power generation, and the net income from export to neighboring countries. The cost of wind generation is a low cost imposed only for the model to prioritize curtailing wind power over solar or hydro when curtailment is necessary. Thus, wind power will always be curtailed before solar power is curtailed or water is spilled. As the model uses hourly averages, all power quantities are in MWh. Thus, Equation (2) defines the objective of the problem to be solved.

3.1.2. Power Balance Constraint

The power balance constraint is given by Equation (3).

$$\sum_{g\in\mathcal{VRE}}p_{g,a,t}+\sum_{g\in\mathcal{MR}}p_{g,a,t}+\sum_{G\in\mathcal{H}}p_{g,a,t}+\Lambda_{a,t}-\sum_{l\in\mathcal{L}}exp_{l,a,t}=D_{a,t}\qquad\forall a\in\mathcal{A},t\in\mathcal{T} \tag{3}$$

where the terms in order are generation from wind, PV, thermal, and hydropower, and the fourth term is the possible load shedding or unserved load. Finally, the fifth term shows the possible export to neighboring countries. Thus, the sum of all generation plus curtailed demand minus export to neighboring countries equals domestic demand.

3.1.3. Variable Renewable Energy (VRE) Constraint

Equation (4) shows that power production from VRE should always be less than or equal to the maximum possible generation during operating hours. The inequality constraint indicates that the generation can be curtailed for flexibility purposes in case of surplus generation. But the curtailment has to be minimized as shown in Equation (2).

$$0\le p_{g,a,t}\le\rho^{max}_{g,a,t}\times cap^{tot}_{g}\qquad\forall g\in\mathcal{VRE},a\in\mathcal{A},t\in\mathcal{T} \tag{4}$$

3.1.4. Hydro Constraints

The constraints for hydropower generation are given by Equations (5) and (6). Constraint (5) enforces energy balance for the reservoirs. The equation shows that the energy content of the reservoir during the starting period of the planning is equal to the sum of energy content one hour before the start minus the discharge minus spillage plus the local inflow plus the energy discharged and spilled from upstream power plants minus the minimum power for irrigation from the upstream power plants, respectively, and can be seen in [26].

Moreover, (6) enforces the energy delay between the up- and downstream power plants. This constraint shows a practical way of modeling the energy flow delays between successive power plants. Assuming a constant time delay for discharge from each upstream power plant to reach the next downstream power plant, the quantity τ^q_k can be expressed in hours (hr^q_k) and minutes (mn^q_k). Equation (6) provides the delayed upstream flow as a weighted average of the discharge between the hours hr_k and hr_{k+1}, as described in [27]. For the spillage delays, a similar expression can be used.

Constraints (7) and (8) show the maximum and minimum generation and minimum spillage from each plant respectively. Particularly, Equation (7) indicates that the electricity production from hydro resources is always greater than the minimum output, representing operational constraints related to minimum water flows or other needs for water from hydro reservoirs. For example, the spillage from hydropower is mandatory for the irrigation of downstream sugar canes, vegetable farmers, etc.

$$m_{g,a,t} = m_{g,a,t-1} - p_{g,a,t} - s_{g,a,t} + v_{g,a,t} + \sum_{k \in F_g^{\mathcal{Q}}} p_{g,a,t-\tau_g^q} + \sum_{k \in F_g^{\mathcal{S}}} s_{g,a,t-\tau_g^q}$$
$$- \sum_{k \in F_g^{\mathcal{Q}}} \rho_k^{min} \times cap_k^{tot} + \sum_{k \in F_g^{\mathcal{Q}}} Q_k^{avg} \left(t \leq \tau_g^q + \sum_{k \in F_g^{\mathcal{Q}}} \frac{60 - mn_k^q}{60} Q_k^{avg} \right) t \leq \tau_i^q + 1 \; \forall g \in \mathcal{H}, a \in \mathcal{A}, t \in \mathcal{T} \quad (5)$$

$$p_{k,a,t-\tau_i^q} = \frac{mn_g^q}{60} p_{k,a,t-h_g^q} + \frac{60 - mn_g^q}{60} p_{k,a,t-h_p^q-1} \qquad \forall k \in \mathcal{F}^{\mathcal{Q}}, a \in \mathcal{A}, t \in \mathcal{T} \quad (6)$$

$$\rho_g^{min} \times cap_g^{tot} \leq p_{g,a,t} \leq cap_g^{tot} \qquad \forall g \in \mathcal{H}, a \in \mathcal{A}, t \in \mathcal{T} \quad (7)$$

$$0 \leq s_{g,a,t} \qquad \forall g \in \mathcal{H}, a \in \mathcal{A}, t \in \mathcal{T} \quad (8)$$

Constraints (9) and (10) force hourly changes in the hydropower output (ramp up and ramp down, respectively) to be less than the maximum ramp rate.

$$p_{g,a,t} - p_{g,a,t-1} \leq \delta_g^{up} \times cap_g^{total} \qquad \forall g \in \mathcal{H}, a \in \mathcal{A}, t \in \mathcal{T} \quad (9)$$

$$p_{g,a,t-1} - p_{g,a,t} \leq \delta_g^{down} \times cap_g^{tot} \qquad \forall g \in \mathcal{H}, t \in \mathcal{T} \quad (10)$$

Equation (12) brings an additional constraint, that the total stored energy in each time step is less than or equal to the maximum.

$$0 \leq m_{g,a,t} \leq m_g^{max} \qquad \forall g \in \mathcal{H}, a \in \mathcal{A}, t \in \mathcal{T} \quad (11)$$

$$\sum_{g \in \mathcal{H}} m_{g,T} = m^{end} \qquad \forall g \in \mathcal{H} \quad (12)$$

3.1.5. Non-Served Load

Equation (13) represents an additional constraint that enforces that the demand curtailed in each time step cannot exceed available demand.

$$0 \leq \Lambda_{a,t} \leq D_{a,t} \qquad \forall a \in \mathcal{A}, t \in \mathcal{T} \quad (13)$$

3.1.6. Reserve Requirements

Reserve requirements can limit the amount of capacity that can be used for generation during normal operation, as some capacity is used to provide reserves. In the Ethiopian power system, there is no rule to provide reserves since the penetration level of VRE is small. In this paper, the reserve requirements are enforced only in the hydropower plants. Constraints (14) and (15) enforce the reserve requirements.

$$\sum_{g \in \mathcal{H}} f_{g,a,t} \geq x_{reg}^{load} \times D_{a,t} + x_{reg}^{vre} \times \rho_{vre,a,t}^{max} \times cap_{vre}^{\text{tot}} \qquad \forall a \in \mathcal{A}, t \in \mathcal{T} \quad (14)$$

$$\sum_{g \in \mathcal{H},} r_{g,a,t} \geq x_{blc}^{load} \times D_{a,t} + x_{blc}^{vre} \times \rho_{vre,a,t}^{max} \times cap_{vre}^{\text{tot}} \qquad \forall a \in \mathcal{A}, t \in \mathcal{T} \quad (15)$$

where constraint (14) shows the frequency regulation reserve requirement, since inertia will be reduced as the penetration of VRE increases, and constraint (15) shows the balancing of the load following reserves, since the variability in and uncertainty of the VRE increase as penetration increases.

Thus, the total requirements for frequency regulation and balancing reserves in each time step t are given by Equations (14) and (15), respectively, as a fraction of the load and variable renewable energy.

The upward and downward reserve provisions are governed by Equations (16) and (17), respectively.

$$p_{g,a,t} + r_{g,a,t} + f_{g,a,t} \leq cap_g^{tot} \qquad \forall g \in \mathcal{H}, a \in \mathcal{A}, t \in \mathcal{T} \tag{16}$$

$$p_{g,a,t} - f_{g,a,t} \geq \rho_g^{min} \times cap_g^{tot} \qquad \forall g \in \mathcal{H}, a \in \mathcal{A}, t \in \mathcal{T} \tag{17}$$

3.1.7. Transmission Line Constraint

Equation (18) shows the power flow constraints from Ethiopia to neighboring countries. Note that this is a unidirectional export of energy from Ethiopia to the other countries.

$$-exp_l^{max} \leq exp_{l,a,t} \leq exp_l^{max} \qquad \forall l \in \mathcal{L}, a \in \mathcal{A}, t \in \mathcal{T} \tag{18}$$

3.1.8. Must-Run Constraint

Equation (19) shows that the must-run resource output in each time period t must exactly equal the available capacity factor times the installed capacity, not allowing for curtailment or the provision of reserves.

$$p_{g,t} = \rho_{g,a,t}^{max} \times cap_g^{total} \qquad \forall g \in \mathcal{G}, a \in \mathcal{A}, t \in \mathcal{T} \tag{19}$$

3.1.9. Full Problem

The total optimization problem is then given by min (2) subject to (3) power balance constraints (4), VRE constraints (5)–(12), hydro constraints (13), non-served load constraints (14)–(17), reserve requirement constraints (18), transmission line constraints (19), and the must-run constraint.

3.2. Model Validation

The model has been validated against historical data by computing the difference between the model's result and historical values for the year 2019. Figure 5 shows the total hydropower generation in Ethiopia from the model and historical data. Because Ethiopia consists mostly of hydropower, this is why it gives good agreement between the two data sets, and the root mean square error (RMSE) becomes 6%.

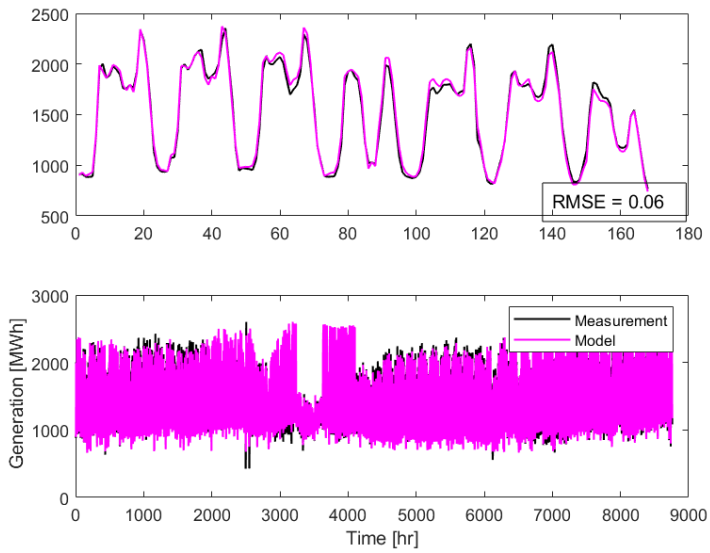

Figure 5. Simulation of hydropower for the year 2019 to validate the model against the historical data.

The results of the model for export to neighboring countries have been validated against measurements. The results are shown in Figure 6. From the figure, it can be seen that the model and historical data have no good agreement because the model has been

simulated based on the transmission capacity and the historical data were simulated from the results obtained based on the market or load needs of the neighboring countries.

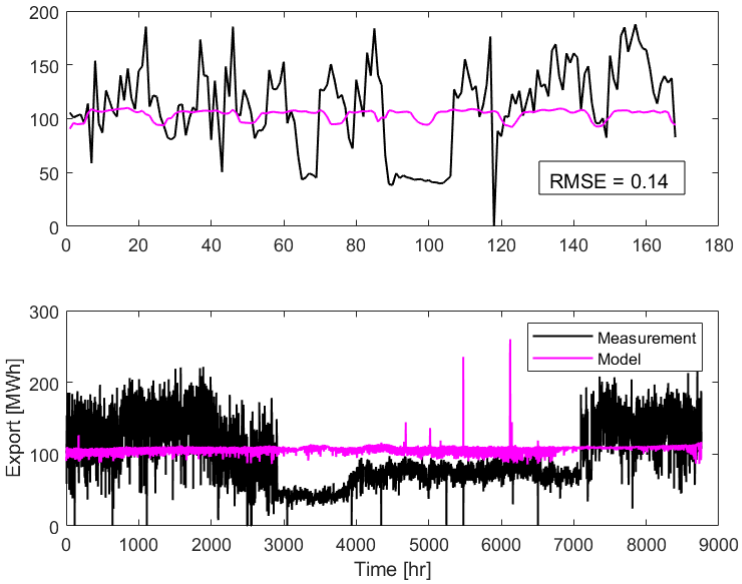

Figure 6. Simulation of export to neighboring countries for the year 2019 to validate the model against the historical data.

3.3. Case Study Setup

The case study was performed using time series data from 2019 as a reference and taking into account the major changes in the Ethiopian power system that are expected until 2030. These changes correspond to an increase in transmission capacity between Ethiopia and neighboring countries, an increase in hydro generation, an increase in load, as well as some increase in thermal generation. The assumptions regarding these and other aspects of the case study are also included and discussed in the following sections.

3.3.1. Minimum Generation Levels

During high wind and PV power generation, production from other power plants can be reduced to its minimum levels depending on the constraints imposed on the power plants in order to decrease the curtailment and balancing challenge. In this simulation, a thermal power plant is considered as a must run and some portion of hydropower is also considered as a must run for minimum generation due to irrigation and other purposes. In the EEP master plan, irrigation was included as one type of load and it is expected to reach 3 TWh/year in 2030. Around 24,000 MWh per day of hydropower is considered as the minimum flow planned by EEP as a reference. In order to see the impact of this minimum generation level on wind curtailment and system balancing, we assumed that the minimum generation will be increased to 129,200 MWh per day. This minimum flow is not spillage and it is the water passing through a turbine for irrigation.

3.3.2. Transmission Capacity to Neighboring Countries

As can be seen in Table 5, there are major changes in the transmission capacity that is expected between Ethiopia and neighboring countries by 2030. There will be a total of 4100 MW of net transmission capacity available in the 2030 horizon year [19]. This is the nominal value of net transmission capacity. However due to planned line outages for maintenance, or because of stability issues such as voltage and rotor angle stability, the nominal value of the transmission line may not be fully used. Thus, in this case study, we assumed an average of 5% hourly line outage to see its impact on wind power curtailment and system balancing.

Table 5. Ethiopia's export capacity projections (MW), 2017–2030 [19].

Year	From	To	Export [MW]
2020	Ethiopia	Djibouti	100
	Ethiopia	Kenya	0
	Ethiopia	Tanzania	0
	Ethiopia	Sudan	200
2030	Ethiopia	Djibouti	100
	Ethiopia	Kenya	2000
	Ethiopia	Tanzania	400
	Ethiopia	Sudan	1600

3.3.3. Annual Energy Generation Assumption

It has been shown that the total annual local demand is 58.5 TWh/year and the maximum export is assumed to be 35.916 TWh/year if the transmission line capacity is fully used. As per the EEP master plan, the average annual inflow of hydropower becomes 64 TWh/year, which was obtained from the multiyear simulation of each hydropower plant conducted by EEP, and 9.3 TWh/year from thermal power plants for the year 2030.

3.3.4. Reserve Assumptions

Table 6 shows the assumed types of reserve requirements and their minimum levels during this study. It also shows the load shedding penalty cost parameters. The minimum level of the regulating and balancing reserve requirements are also assumed in the same table. In this case study, we assumed an increase in regulating reserves for VREs from 1% to 3% to see the impact on wind power curtailment and system balancing. Table 7 shows the contribution of each technology to the required reserves provision. In the same table, the ramp rate of each technology is shown.

Table 6. Security information requirements for keeping reserves and penalty for load shedding.

Type of Reliability Requirement	Minimum Level Required	Penality Cost
Load shedding	-	2000 $/MWh
Regulating reserve	1% Load + 1% VRE	binding
Balancing reserve	5% Load + 15% VRE	binding

Table 7. Reserve contributions of generation technologies.

Technology	Contribution to Regulating Reserves [% of Max Output]	Contribution to Balancing Reserves [% of Max Output]	Ramp rate [% of Maximum Output]
Hydropower	5	20	100
Wind	0	0	-
Solar	0	0	-
Thermal	0	0	-

3.3.5. Scenarios Setup

Different scenarios have been considered in order to see the impacts of operational constraints on wind power curtailment and system balancing challenges with different wind penetration levels. These different wind penetration levels and operational constraints are configured as scenarios and shown in Table 8. The table contains 24 scenarios which are is composed of three wind penetration levels and operational constraints such as transmission capacity to neighboring countries, daily minimum generation of hydropower for irrigation, and regulation reserve requirements. For example, scenario 9 is equivalent to

the W5000-MP0-R1-TL0 model configuration in the table. The description of each of the model configurations to be used later are given as follows:

1. Wind power scenario
   - W3844: 3844 MW scenario (14.5% generation share).
   - W5000: 5000 MW scenario (17.8% generation share).
   - W8000: 8000 MW scenario (25.2% generation share).
2. Minimum power generation (see Section 3.3.1)
   - MP0: planned minimum power generation (24,000 MWh/day).
   - MP1: increased minimum power generation (129,200 MWh/day).
3. Net transmission line capacity (see Section 3.3.2)
   - TL0: the full nominal NTC capacity is used.
   - TL1: reduced transmission line capacity is used.
4. Regulation reserve (see Section 3.3.4)
   - R0: planned regulating reserve is used.
   - R1: increased regulating reserve is used.

Table 8. Scenario table for wind power curtailment analysis.

Wind Scenario		**W3844**		**W5000**		**W8000**	
Minimum Power		**MP0**	**MP1**	**MP0**	**MP1**	**MP0**	**MP1**
Transmission Capacity	Regulating Reserve						
TL0	R0	1	2	3	4	5	6
	R1	7	8	9	10	11	12
TL1	R0	13	14	15	16	17	18
	R1	19	20	21	22	23	24

4. Result and Discussion

In this section, the results of the case study are presented and discussed. The study has considered different configurations of wind penetration level with some operational constraints to analyze the maximum curtailment of wind power and its effect on system balancing. The configurations of the scenarios are abbreviated as a code for simplicity to explain the results. For example, the configuration code W5000-MP0-R0-TL1 refers to the case with a 5000 MW wind penetration level and 24,000 MWh per day minimum hydropower generation for irrigation, considering 1% regulating reserves, and a 5% reduction in transmission line capacity to neighboring countries. MP shows how the daily minimum hydropower generation affects the flexibility of hydropower and system balancing. Furthermore, R shows how the regulating reserve requirement affects the mentioned objectives, and finally TL shows what the effect of transmission line capacity will be on the system balancing and wind power curtailment.

Table 9 shows the simulation results for wind power curtailment as a percentage of available annual generation capacity for different configurations of operational constraints and wind power scenarios. This means that the simulation results were obtained from the combination of wind penetration level, net transmission line capacity to neighboring countries, daily minimum hydropower generation for irrigation, and regulation reserve constraints. The maximum curtailment is observed during the configuration W8000-MP1-TL1-R1. This maximum curtailment mainly happened due to an increased daily minimum generation of hydropower for irrigation and reduced transmission line capacity.

Table 9. Wind power curtailment as a % of available generation.

Wind Scenario		**W3844**		**W5000**		**W8000**	
Minimum Power		**MP0**	**MP1**	**MP0**	**MP1**	**MP0**	**MP1**
Transmission capacity	Regulating reserve						
TL0	R0	0	0	0	0.36	1.18	5.76
	R1	0	0.03	0	0.62	0	7.51
TL1	R0	0	0.05	0	0.68	2.12	8.12
	R1	0	0.2	0	1.1	1.37	9.8

The net transmission line capacity to neighboring countries significantly affects the wind power curtailment. Decreasing the transmission capacities from full capacity to historical (reduced) values significantly increases curtailment, irrespective of the other configurations. For example, from Table 9, in the case of W8000-MP1-R0-TL0, curtailment increases from 5.76% to 8.12% because of transmission line congestion.

It can further be concluded from Table 9 that the regulating reserve will limit the curtailment of wind power to some extent. The effect of the regulating reserve is observed from two directions, i.e., from up- and downregulation depending on the daily minimum generation of hydropower. During high daily minimum hydropower generation, the curtailment is increased due to the downregulation reserve, which was kept from hydropower, and this reserve increases the minimum hydropower generation. The increment in minimum generation in turn increases curtailment. On the other hand, during low daily minimum hydropower generation, the curtailment is decreased due to the upregulation reserve, which was was kept from hydropower. This decreases the generation capacity of the hydropower plants. Then, decreasing the hydropower generation capacity will open the door for wind power to be utilized, which in turn decreases the curtailment.

In general, the low daily minimum hydropower generation does not have much impact on the flexibility of hydropower, so when we increase the regulating reserve, the hydropower decreases from its maximum generating capacity, giving room for more wind power to be generated, which leads to a decrease in curtailment, and the reverse is true for high minimum power. In summary, the regulating reserve has a small impact on curtailment compared to the other two constraints.

For the case of MP, the daily minimum hydropower generation for irrigation leads to curtailment by forcing some parts of the power plants to operate as base load generators. This minimum power generation will limit the flexibility of hydropower for accommodating wind power. From Table 9, for the case of W8000-MP0-TL1-R1, the curtailment was increased from 1.37% to 9.8% due to an increment in the daily minimum generation of hydropower irrespective of other constraints. Thus, it can be concluded that increasing the daily minimum power generation significantly reduces the flexibility of hydropower, which results in higher curtailment and increases the balancing challenge.

Finally, the wind power in the grid has an impact on curtailment depending on its penetration level. The simulation result from Table 9 indicates that the maximum curtailment becomes 0.2%, 1.1%, and 9.8% of the wind power annual generation capacity for penetration levels of 3844 MW, 5000 MW, and 8000 MW, respectively, irrespective of the other operational constraints. These results confirm that as the penetration level of wind power increases, its curtailment also increases. The duration curve shown in Figure 7 also depicts the maximum magnitude of wind power curtailment and how much time per year curtailment occurs.

In this part, the system balancing challenges during high wind and low consumption are to be discussed. The worst balancing challenge can be observed during high curtailment, at which wind is at its peak and consumption is at a low level. This result can be seen in the setup W8000-MP1-TL1-R1 and is depicted in Figure 8. This figure shows a situation

that is not in balance as there is extra generation over several hours, particularly on the first two days. This kind of situation is physically impossible, so the challenge has to be managed either by exporting, storing, or curtailing to bring the system into balance. In this paper, the system comes into balance by exporting and curtailing the extra wind energy. After curtailing the wind power, the result is shown in Figure 9 indicating that the system is balanced.

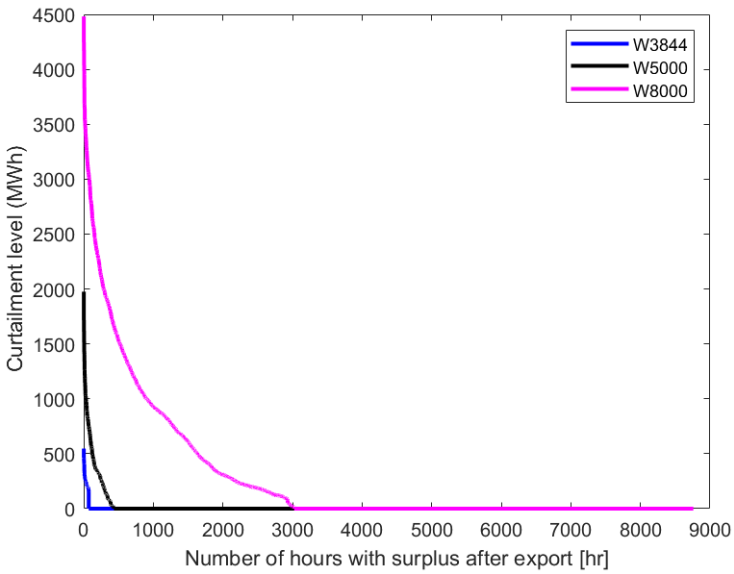

Figure 7. Duration curves of wind curtailment for 8000 MW, 5000 MW, and 3844 MW penetration levels shown in green color in Table 9.

From Figure 10, one can easily observe that there is no curtailed wind power for the case of W8000-MP0-TL1-R1. This is due to the high flexibility of hydropower. This high flexibility of hydropower resulted from the low daily minimum power generation constraint.

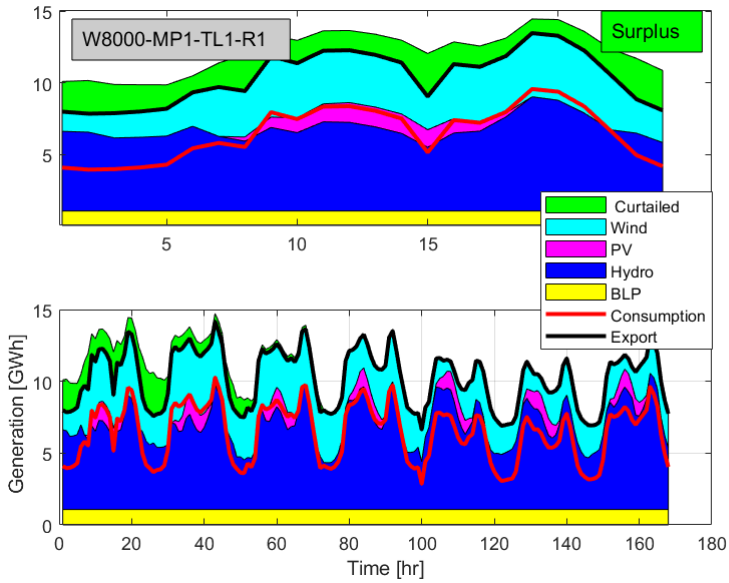

Figure 8. Consumption for the third week of January. The figure on the top shows the first day of the week and the bottom is the total week. The figure shows the magnitude of curtailed wind power for the case of high daily minimum power generation. It also shows the summation of curtailed wind, wind, PV, hydropower, base load power plant (BLP) or thermal power plants, local consumption, and export.

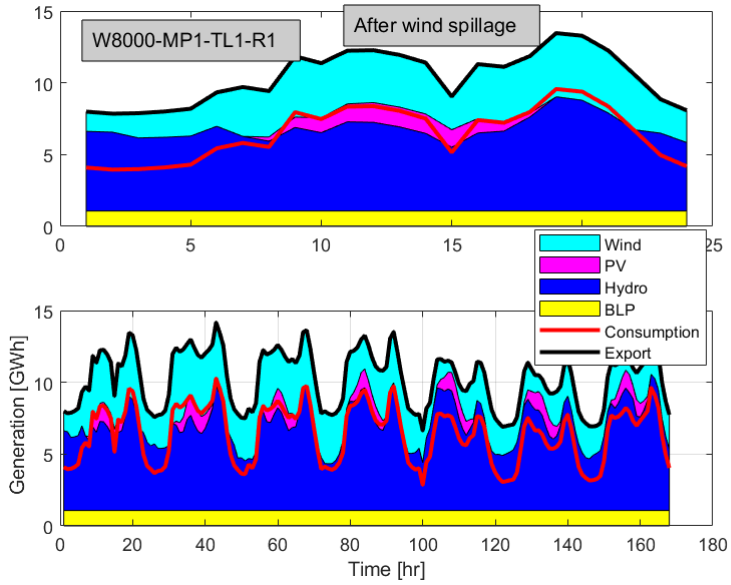

Figure 9. Consumption for the first week of January. The figure on the top shows the first day of the week and the bottom is the total week. The figure shows the balanced system after spilling extra wind power for the case of high daily minimum power generation. It also shows the summation of wind power, PV, hydropower, base load power plant (BLP) or thermal power plants, local consumption, and export.

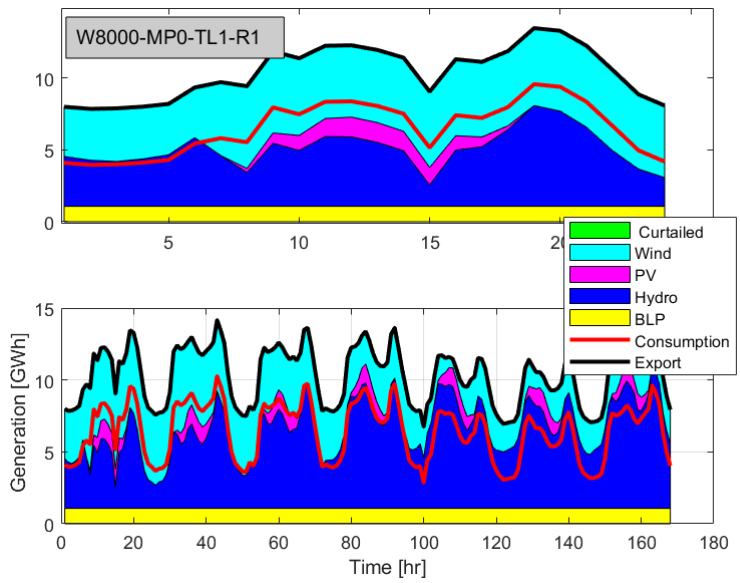

Figure 10. Consumption for the third week of January. The figure on the top shows the first day of the week and the bottom is the total week. The figure shows the balanced system due to high flexibility of hydropower in the case of low daily minimum power generation. It also shows the summation of curtailed wind, wind, PV, hydropower, base load power plant (BLP) or thermal power plants, local consumption, and export.

As shown in Figure 11, there are 3024 h/year with curtailment, and the total energy curtailed is 2.52 TWh/year during the configuration W8000-MP1-TL1-R1. This means that 9.8% of all wind power is spilled. Economically, this means that wind energy becomes 9.8% more expensive as not all generation is used. There are other possibilities to use the energy, for example, exporting if a sufficient transmission line is available; charging electric vehicles, which is an upcoming agenda for Ethiopia; and any other alternatives.

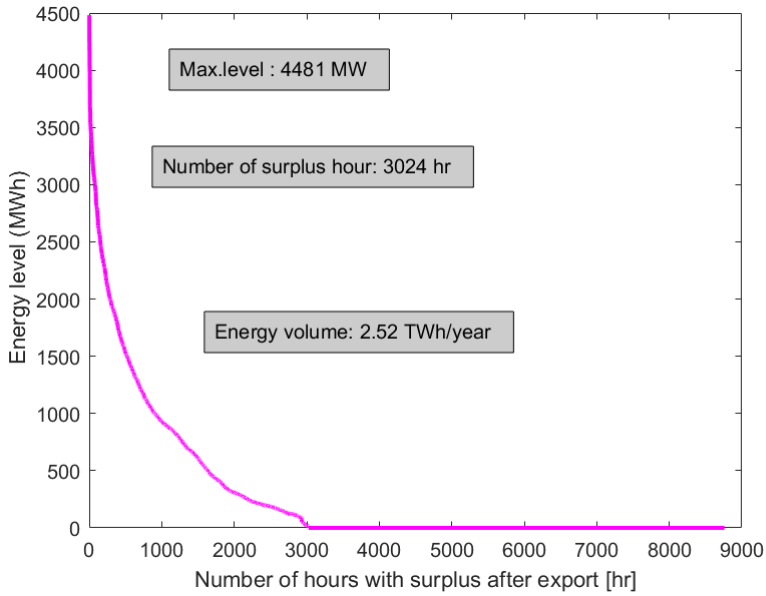

Figure 11. Duration curve of wind curtailment during the worst scenario or W8000-MP1-R1-TL1 system configuration. It shows how much wind power is curtailed and number of hours of curtailment per year.

One of the methods to reduce the wind power curtailment and system balancing challenge is exporting the extra energy to neighboring countries. Figure 12 shows the duration curve of export for each wind scenario. From the figure, one can observe that as integration increases export also increases as much as possible relative to the transmission capacity.

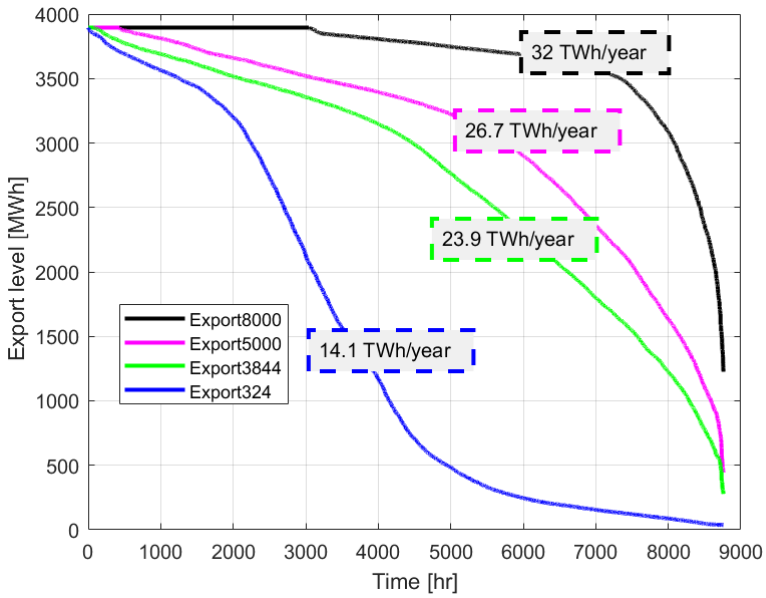

Figure 12. Duration curve for export during each wind scenario. It shows how much energy is exported during each wind power scenario. The export is high during the 8000 MW scenario and low during the existing or 324 MW wind scenario.

5. Conclusions

We have developed and used an hourly dispatch model for the Ethiopian power system to study the amount of wind power curtailment and identify the system balancing challenge for the future Ethiopian power system with 3844 MW, 5000 MW, and 8000 MW wind penetration levels.

The wind curtailment and system balancing challenge is worse when reduced transmission capacity, high daily minimum hydropower generation, and regulation reserve are considered. During this configuration, the wind curtailment becomes 9.8% of the available annual generation capacity for wind power. The regulation reserve requirement has a small impact on curtailment and the system balancing challenge compared to the other constraints.

The most important factors influencing curtailment were the transmission capacity and the minimum generation of hydropower. The daily minimum generation of hydropower limits the flexibility of hydropower, which leads to higher curtailment and worsens the system balancing challenge.

The capacity of wind power in the grid also highly affects the curtailment of wind power. As the magnitude of wind power increases, the curtailment also increases irrespective of other parameters. The curtailment in the system not only affects the operation of the system but also the cost of wind power. This means that as the curtailment increases, the cost of wind power also increases as not all energy from wind is used. In this paper, during the configuration of W8000-MP1-T1-R1, the cost of the wind power increased by 9.8%.

Thus, when integrating wind power into any national grid, the curtailment and balancing challenges have to be studied and the worst scenarios should be identified. In this paper, the worst challenges occurred when there was high daily minimum power and reduced transmission lines to neighboring countries, whereas the reserve requirement had a small impact. Furthermore, the cost of wind power also increases with the same percentage of curtailment.

6. Future Work

The next plan is to conduct a reliability analysis of the Ethiopian power system with different wind integrations and transmission lines.

Author Contributions: K.L.N.: Conceptualization, Methodology, Software, Visualization, Writing—Original Draft Preparation, Review and Editing. L.S.: Conceptualization, Supervision, Writing—Review and Editing. M.M.: Conceptualization, Supervision, Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Swedish International Development Cooperation Agency (SIDA).

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are unavailable due to privacy or ethical restrictions.

Acknowledgments: The authors would like to thank (1) Ethiopian Electric Power (EEP), who enabled this research by generously giving us their generation data; and (2) the Swedish International Development Cooperation Agency for funding this research.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

Description of nomenclature

Indices and Sets

$\mathcal{H} \in \mathcal{G}$	where $\mathcal{H}$ is a subset of hydroelectric generators
$\mathcal{MR} \in \mathcal{G}$	where $\mathcal{MR}$ is a subset of must run generators
$\mathcal{VRE} \in \mathcal{G}$	where $\mathcal{VRE}$ is a subset of curtailable Variable Renewable Energy (VRE) resources
τ_g^q	where τ_g^q is a time delay for the discharged energy of the upstream power plant to reach the downstream power plant g
τ_g^s	where τ_g^s is a time delay for the spilled energy of the upstream power plant to reach the downstream power plant g
$a \in \mathcal{A}$	where a denotes time step in days and $\mathcal{A}$ is the set of days in the planning horizon

Indices and Sets

F_g^Q	where F_g^Q is a set of upstream hydropower stations for station g (discharge)
F_g^S	where F_g^S is a set of upstream hydropower stations for station g (spillage)
$g \in \mathcal{G}$	where g denotes a technology and $\mathcal{G}$ is the set of available technologies
$l \in \mathcal{L}$	where l denotes a transmission line and $\mathcal{L}$ is the set of available transmission lines
$t \in \mathcal{T}$	where t denotes a time step and $\mathcal{T}$ is the set of time steps over which grid operations are modeled

Decision variables

$\Lambda_{a,t}$	where $\Lambda_{a,t}$ is a non-served energy or shed load for day a, at time t [MWh]
$exp_{l,a,t}$	where $exp_{l,a,t}$ is a power flow on line l for day a, at time t between Ethiopia and neighboring countries [MWh]
$f_{g,a,t}$	where $f_{g,a,t}$ is a frequency regulation contribution for reserve from hydropower of station g for day a, at time t [MWh]
$m_{g,a,t}$	where $m_{g,a,t}$ is a reservoir level of hydropower of station g for day a, at time t [MWh]
$p_{g,a,t}$	where $p_{g,a,t}$ is an hourly generation from technology g for day a, at time t [MWh]
$r_{g,a,t}$	where $r_{g,a,t}$ is a balancing reserve from hydropower of station g for day a, at time t [MWh]
$s_{g,a,t}$	where $s_{g,a,t}$ is a spillage capacity of reservoir hydropower of station g for day a, at time t [MWh]

Parameters

m^{end}	End or final reservoir level [MWh]
δ_g^{down}	Maximum ramp-down rate per time step as percentage of installed capacity of power plant g [%/hr]
δ_g^{up}	Maximum ramp-up rate per time step as percentage of installed capacity of power plant g [%/hr]
$\rho_{g,a,t}^{max}$	Maximum available generation per unit of installed capacity during time step t for technology g [%]
ρ_i^{min}	Minimum stable power output per unit of installed capacity for technology g of [%]
c_{ns}	Cost of non-served energy/demand curtailment [USD/MWh]
c_t	Cost of generating thermal power plants g [USD/MWh]
c_w	Cost of generating wind power plants [USD/MWh]
cap_g^{tot}	where cap_g^{tot} is a total installed capacity of technology g MW
$D_{a,t}$	where $D_{a,t}$ is an electricity demand for day a, at time t [MWh]
exp_l^{max}	Maximum power flow on line l between Ethiopia and neighboring countries [MW]
m_g^{max}	maximum reservoir level of power plant g [MWh]
Q_g^{avg}	Average inflow of water to each reservoir per hour [MWh]
x_{blc}^{load}	Operating (balancing) reserve requirement as a fraction of forecasted demand in each time step [%]
x_{reg}^{load}	Frequency regulation reserve requirement as a fraction of forecasted demand in each time step [%]
x_{blc}^{vre}	Operating (balancing) reserve requirement as a fraction of forecasted variable renewable energy generation in each time step[%]
x_{reg}^{vre}	Frequency regulation reserve requirement as a fraction of variable renewable energy generation in each time step [%]

References

1. IEA. IEA Wind Task 25 DESIGN and Operation of Power Systems with Large Amounts of Wind Power Design and Operation of Power Systems with Large Amounts of Wind Power Final Summary Report , IEA WIND Task. 2014. Available online: http://www.vttresearch.com/impact/publications (accessed on 15 June 2021).
2. Basit, A.; Altin, M.; Hansen, A.D.; Sørensen, P.E. Balancing Modern Power System with Large Scale of Wind Power. China Wind Power (CWP), Cwp. 2014. Available online: http://orbit.dtu.dk/files/105380608/Balancing-modern-Power-System.pdf (accessed on 10 February 2022).
3. Söder, L. Simplified analysis of balancing challenges in sustainable and smart energy systems with 100% renewable power supply. *Wiley Interdiscip. Rev. Energy Environ.* **2016**, *5*, 401–412. [CrossRef]
4. Söder, L. Possibilities for Balancing Wind Power Variations. 2010. Available online: http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A467461anddswid=6343 (accessed on 1 February 2021).
5. Chandler, H. A Guide to the Balancing Challenge. 2011. Available online: https://www.iea.org/ (accessed on 25 March 2022).
6. Balancing Power Systems with Large Share of Wind Power Task 25 Fact Sheet. Available online: https://iea-wind.org/task25/ (accessed on 25 March 2022).

7. Bird, L.; Cochran, J.; Wang, X.; Bird, L.; Cochran, J.; Wang, X. *Wind and Solar Energy Curtailment: Experience and Practices in the United States*; U.S. Department of Energy Office of Scientific and Technical Information: Golden, CO, USA, 2014.
8. Nycander, E.; Söder, L.; Olauson, J.; Eriksson, R. Curtailment analysis for the Nordic power system considering transmission capacity , inertia limits and generation flexibility. *Renew. Energy* **2020**, *152*, 942–960. [CrossRef]
9. Mc Garrigle, E.V.; Deane, J.P.; Leahy, P.G. How much wind energy will be curtailed on the 2020 Irish power system? *Renew. Energy* **2013**, *55*, 544–553. [CrossRef]
10. Qi, Y.; Dong, W.; Dong, C.; Huang, C. Fixing Wind Curtailment with Electric Power System Reform in China. 2018. Available online: https://www.brookings.edu/wp-content/uploads/2018/04/fixing-wind-curtailment-with-electric-power-system-reform-in-china.pdf (accessed on 25 January 2021).
11. Lew, D.; Bird, L.; Milligan, M.; Speer, B.; Wang, X.; Carlini, E.M.; Estanqueiro, A.; Flynn, D.; Gomez-lazaro, E.; Menemenlis, N.; et al. Wind and Solar Curtailment. International Workshop on Large-Scale Integration of Wind Power Into Power Systems, September 2013. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.390.1983andrep=rep1andtype=pdf (accessed on 29 August 2020).
12. Villamor, L.V.; Avagyan, V.; Chalmers, H. Opportunities for reducing curtailment of wind energy in the future electricity systems: Insights from modelling analysis of Great Britain. *Energy* **2020**, *195*, 116777. [CrossRef]
13. Alham, M.H.; Elshahed, M.; Ibrahim, D.K.; El Zahab, E.E.D.A. Optimal operation of power system incorporating wind energy with demand side management. *Ain Shams Eng. J.* **2017**, *8*, 1–7. [CrossRef]
14. Sousa, J.; Martins, A. Optimal renewable generation mix of hydro, wind and photovoltaic for integration into the Portuguese power system. In Proceedings of the International Conference on the European Energy Market, EEM, Stockholm, Sweden, 27–31 May 2013; pp. 1–6. [CrossRef]
15. Farahmand, H.; Doorman, G.L. Balancing market integration in the Northern European continent. *Appl. Energy* **2012**, *96*, 316–326. [CrossRef]
16. Graabak, I.; Korpås, M. Balancing of Variable Wind and Solar Production in Continental Europe with Nordic Hydropower—A Review of Simulation Studies. *Energy Procedia* **2016**, *87*, 91–99. [CrossRef]
17. Korpås, M.; Trötscher, T.; Völler, S.; Tande, J.O. Balancing of Wind Power Variations Using Norwegian Hydro Power. *Wind. Eng.* **2013**, *37*, 79–95. [CrossRef]
18. Askeland, K.; Bozhkova, K.N.; Sorknæs, P. Balancing Europe: Can district heating affect the flexibility potential of Norwegian hydropower resources? *Renew. Energy* **2019**, *141*, 646–656. [CrossRef]
19. National Electrification Program. National Electrification Program 2.0. Thematic Program Document. October 2019; p. 49. Available online: https://www.powermag.com/wp-content/uploads/2020/08/ethiopia-national-electrification-program.pdf (accessed on 20 June 2021).
20. GTP II. Federal Democratic Republic of Ethiopia Volume I: Main Text. World Bank Group, I(GTP II). Available online: https://www.greenpolicyplatform.org/national-documents/ethiopia-growth-and-transformation-plan-ii-gtp-ii (accessed on 15 June 2020).
21. Nefabas, K.L.; Söder, L.; Mamo, M.; Olauson, J. Modeling of ethiopian wind power production using era5 reanalysis data. *Energies* **2021**, *14*, 2573. [CrossRef]
22. NREL. System Advisory Model. Available online: https://sam.nrel.gov/ (accessed on 12 January 2022).
23. Consumption, E.; Resources, E. Sudan. 2013–2016. Available online: https://wedocs.unep.org/bitstream/handle/20.500.11822/20596/Energy-profile-Sudan.pdf?sequence=1andisAllowed=y (accessed on 10 April 2023).
24. Ethiopin Electric Power System Development II. EEP, Addis Ababa City, Ethiopia. 2023, *unpublished work*.
25. Model Factsheets. Available online: https://openenergy-platform.org/factsheets/models/ (accessed on 25 August 2022).
26. Kouveliotis-Lysikatos, I.; Marin, M.; Amelin, M.; Soder, L. Exploring Multitemporal Hydro Power Models of the Nordic Power System using Spine Toolbox. In Proceedings of the UPEC 2020—2020 55th International Universities Power Engineering Conference, Torino, Italy, 1–4 September 2020. [CrossRef]
27. Amelin, M. Efficient Operation and Planning of Power Systems. 2011. Available online: https://www.kth.se/social/files/552fa36ff276542768d34c34/Efficient%20Operation%20and%20Planning%20of%20Power%20Systems%20-%202011.pdf (accessed on 20 March 2019).