Modeling A Notional Carbon-Free Power Grid with 24-hour Dispatch and Power Flow

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2023 International Conference on Future Energy Solutions (FES) | 979-8-3503-3230-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/FES57669.2023.10183308

***Abstract*—This paper proposes methods of DC and AC power flow development and the battery configuration for a notional carbon-free power grid. Facing climate change, many governments are seeking carbon-free generation technologies, so there is a great need for carbon-free grid modeling. In this paper, a public synthetic ERCOT model is used as a base case. Also, the actual renewable generation and load profiles in a summer heavy load day from EIA are utilized in the modeling. First, all loads are scaled to project the actual EIA load profile. Second, all fossil-fuel generators in the base case are replaced by the combinations of renewables and batteries, while hydro and nuclear remain unchanged. Third, the PV and wind power are scaled according to the actual EIA generation profile, with the consideration of battery energy balance and reasonable PV/capacity ratio in the future. Finally, AC power flow results of the developed dispatches are obtained by PSS/E. Meanwhile, necessary battery capacity and initial SoC are estimated based on the dispatches. Even though achieving carbon-free power grid is very challenging, the developed cases in this paper can provide insights for the related research. Also, the methods to develop dispatches and configure batteries can benefit the researchers who need to build the carbon-free model in a different grid.**

Keywords— Carbon-free Grid, Dispatch Development, Power Flow Case Development, Minimum Battery Capacity

I. INTRODUCTION

Facing the climate change and finiteness of fossil fuel, many countries have published their targets on carbon emissions [1]. Thus, there is a great need to have the carbon-free power grid dispatch and power flow, as well as the method to size the required battery storage. The carbon-free grid is challenging but necessary. The requirements to achieve 100% variable renewable energy are summarized in [2]. Potential issues in the power system with no fossil-fuel are discussed in [3]. There are several trials of carbon-free power grids. Ref [4] reports a 100% carbon-free micro-grid project located in Rokkasho in Japan. A carbon-free electrical energy regional model on Jeju Island in South Korea is introduced in [5]. An hourly energy balance analysis is presented in a 100% renewable energy scenario in Australia [6]. All these trials provide valuable information for a carbon-free power grid. However, the method to develop dispatches and power flow cases is not proposed, and the necessary battery capacities for the carbon-free grid is not mentioned.

With the goal of dealing with the issues mentioned above, as well as providing students the opportunity to learn the simulation tool and the basics of energy balance, power flow, and energy storage system, a project to solve these practical issues is assigned in a graduate course at the University of Tennessee, Knoxville Department of Electrical Engineering and Computer Science. With the collaboration between students and instructors, finally, an implementable method for developing 24-hour power dispatches and power flows of the carbon-free grid is proposed. Additionally, the necessary battery capacity is estimated to ensure energy balance during the whole day.

The remainder of this paper is organized as Fig. 1. In Section II, the data for the study is first prepared. ERCOT model from Texas A&M University is used as the base power flow case. Typical 24-hour PV, wind, and load profiles are obtained from the EIA website. Section III develops 24-hour DC dispatches. The hydro and nuclear outputs are constant in 24 hours. The fossil-fuel generators are replaced by the combinations of PV, wind, and battery. The 24-hour PV, wind, and load profiles are scaled to make the power and energy balance. Section IV further introduces AC power flow development. Based on the developed DC dispatches, hourly power flow cases without fossil-fuel generators are built, and then PSS/E is used to solve these cases for the power flow results. Section V proposes the method to configure the battery. Based on the DC dispatches, the battery charging and discharging curve can be obtained. The necessary battery capacity and initial SoC (State of Charge) are estimated.

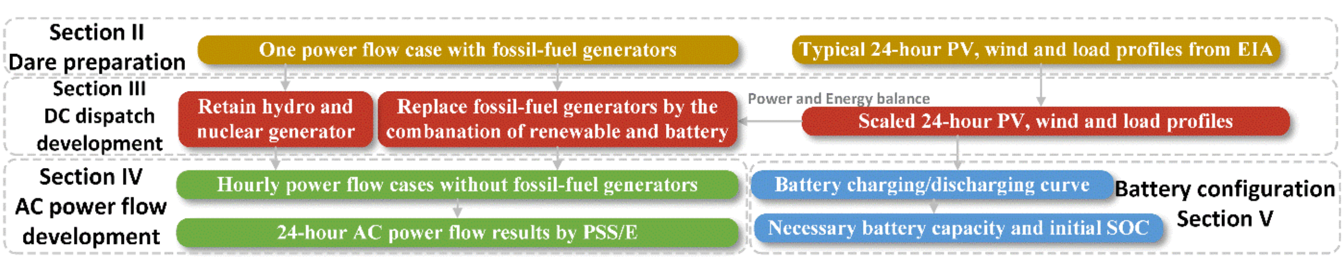

Fig. 1. Process of the power flow case development and battery configuration.

II. Introduction to Synthetic ERCOT System and EIA Data

A. Synthetic ERCOT System

U.S. Power Grid models require non-disclosure agreements to be in place prior to accessing Critical Energy/Electric Infrastructure Information (CEII). However, the 2000-bus synthetic Texas model developed by Texas A&M University has been built from publicly available data and actual power system statistical information. It represents a fictitious transmission network without requirements of special access to use [7]. The 2000-bus PSS/E power flow base case data has a total of 544 machines, including 87 renewable machines. The total base case load is 67,109 MW.

Since the main purpose of this study is to develop carbon-free power flow cases, all fossil fuel-based generators are replaced with wind and solar powered machines, so the fuel type must be determined. Using information available on the U.S. Energy Information Administration (EIA) website [8], four nuclear power machines are identified in the synthetic model based on the bus name and machine size, which are shown in Fig. 2. The total active power generation from the two Glen Rose machines is 2,430 MW, which matches the nameplate capacity from the EIA data. Likewise, the two Wadsworth machines' active power generation is 2,708 MW. The overall nuclear generation total is 4,825 MW. Another important thing to note is that the Wadsworth generator located at bus 7098 is the system slack bus. This becomes important during the tuning process of the 24-hour dispatch cases.

Additionally, some carbon-free generation is already included in the base case such as hydro, wind, and some solar. The hydro generators are determined if the machine's dynamic governor model is 'HYGOV'. A total of twenty hydro-based machines are identified with a total active power of 2,436 MW. The pre-existing wind and solar are not calculated since they will be included with the new renewable machines. Any remaining machines that are not explicitly identified are considered fossil-fuel-based generation and are converted to renewable.

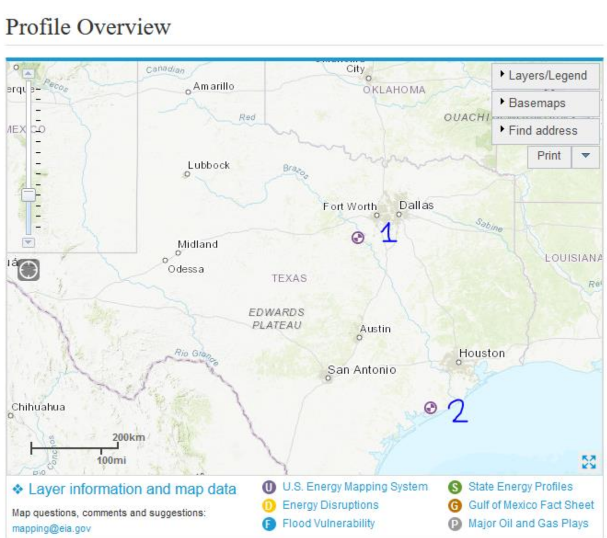

Fig. 2. Nuclear Stations (1) Glen Rose, and (2) Wadsworth.

B. 24-hour Generation and Demand Data

To create the 24-hour dispatch cases, a single day load profile is retrieved from the EIA website for the Electric Reliability Council of Texas (ERCOT) region [9]. In this paper, August 5, 2021 is chosen since it represented a typical summer day with a notable contribution of wind and solar power generation. The generation and demand profiles are in Figs. 3-4.

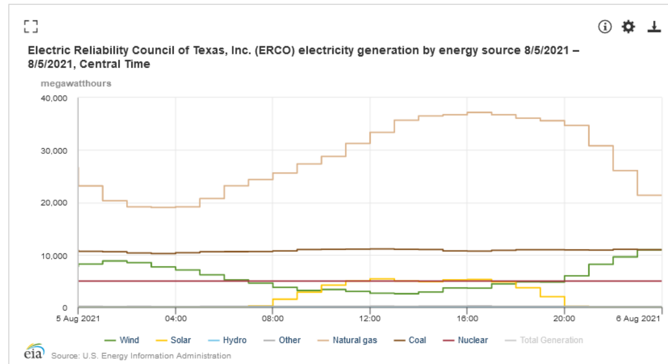

Fig. 3. ERCOT generation profile by fuel-type on August 5, 2021.

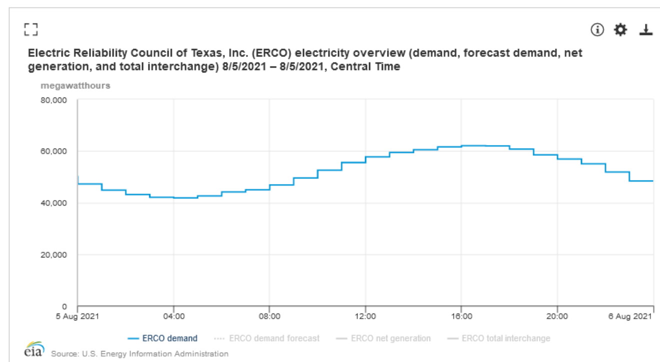

Fig. 4. ERCOT demand profile on August 5, 2021.

The peak demand on the chosen day is 62,071 MW at 17:00. In ERCOT, most of the energy demand is satisfied by natural gas and coal generation. These load and generation profiles are further used to scale the PSS/E synthetic case model to create 24 hourly snapshots for one day.

III. 24-Hour Dispatch Development For Carbon-free Synthetic ERCOT Power System

In this section, carbon free-grid dispatches are developed based on the synthetic ERCOT model and EIA data, in which all the existing gas and steam generators are replaced by renewables and battery storage. The typical load and generation profiles from EIA are scaled to fit the base synthetic ERCOT model.

A. Load Scaling

To avoid transmission expansion in this study, the transmission line power should not exceed the transmission line limit. Thus, the base case of synthetic ERCOT is used as the peak load case. The peak demand on the selected day is less than the total case load, so the load profile is linearly scaled so that the peak is equal to the case load. To achieve the above, the load scaling factor (1) is used to multiply the 24 hours load demand data obtained from EIA. Fig. 5 shows the scaled EIA load demand (black curve), whose peak load is same load as the base synthetic ERCOT PSS/E model.

$$Load\ scaling\ factor = \frac{Total\ load\ in\ the\ base\ case}{Peak\ EIA\ load} \quad (1)$$

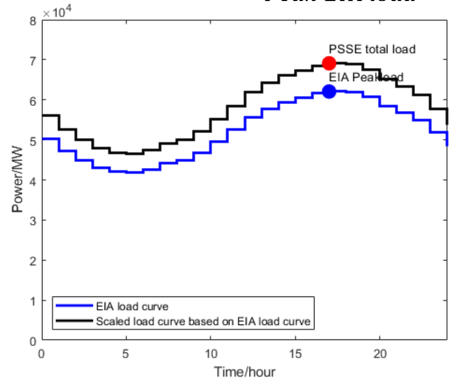

Fig. 5. EIA original load and scaled load profiles.

B. Renewable Scaling

Fig. 6 shows the initial carbon-free 24-hour dispatches after just the load scaling. It can be found that the total generation values based on EIA typical renewable profile are not enough to support the load, so the renewables need to be scaled for the power balance.

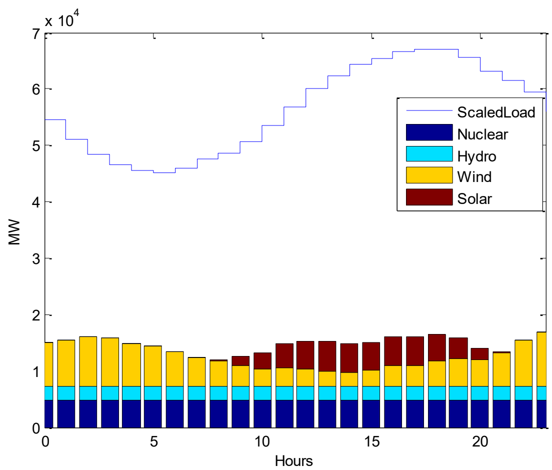

Fig. 6. 24-hour dispatches after just scaling the load.

In addition to scaling the load, the initial solar and wind profiles are also scaled while keeping the nuclear and hydro power constant. The nuclear power has a total size of 4825MW while the hydro power has a total size of 2436MW.

Considering the different installation speeds of PV and wind, the further carbon-free grid should have different capacities of PV and Wind. Because of uncertainty in the technology development, market, and policy, it is difficult to know the exact capacity numbers of PV and wind in the future carbon-free grid, so it is assumed that the future solar would be approximately twice that of wind in this paper. Thus, the solar power is scaled such that the peak solar power is twice the peak wind. The original peak solar is 5408MW and the original peak wind is 9585MW from EIA data, so the initial solar scaling factor is then used to multiply the 24-hours solar profile. The initial solar scaling factor is calculated as follows:

$$Initial\ solar\ scaling\ factor = \frac{2 * \max(windpower)}{\max(solarpower)} \quad (2)$$

The dispatch after scaling just the solar is shown in Fig 3. From Fig 3, clearly, the solar and wind power should be further increased to meet the load demand.

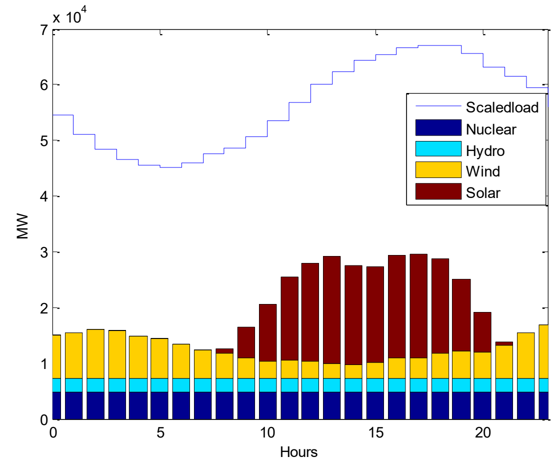

Fig. 7. Dispatch after scaling only the solar.

Because different battery energy conditions and configurations could result in different dispatches, in this paper we further assumed that the battery has the energy balance in 24 hours, which means the charging energy is the same as the discharging one. Also, the battery has enough necessary initial SoC and capacity to achieve the energy balance. Then, the total solar and wind power are scaled such that the battery's net charging and discharging energy are equal. To achieve the above target, we iterate through many discrete scaling factors for PV and wind in a reasonable region. The final scaling factor for PV and wind power is found as 3.8259. Finally, the PV and wind profiles in Fig. 7 are multiplied by this scaling factor, and then the 24-hour profiles can be obtained, as shown in Fig.8.

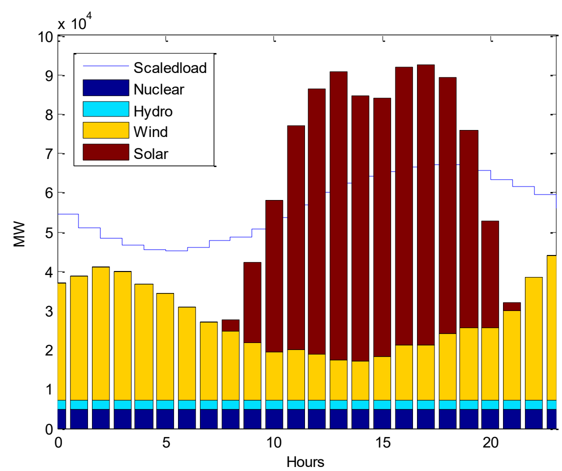

Fig. 8. Final scaled dispatch.

In Fig.8, the scaled renewable power generation in the selected typical day fluctuates, where the solar power reaches the higher points near noon while the wind power peak occurs at the midnight. However, the peak load comes in the afternoon. Thus, the battery is necessary to use to mitigate the gap.

IV. 24-Hour AC Power Flow Cases Development and Results

This section presents the creation of the 24-hour power flow cases and their AC power flow results. All the simulation-related operations in this section are achieved by PSS/E python API.

In this paper, renewables are regarded as the combination of PV, wind, and battery at the locations originally with the traditional gas and steam generators. According to the total generation and load profiles, the single load and generator output value of each hour can be assigned.

Each load is considered with the constant proportion of the total load among 24 hours. Based on the base synthetic ERCOT case, one could have the load active power of i^{th} hour as:

$$\begin{aligned} &\mathit{Load\ active\ power\ of\ i^{th}\ hour} \\ &= \frac{\mathit{Total\ load\ power\ of\ i^{th}\ hour}}{\mathit{Total\ load\ power\ of\ base\ case}} \cdot \\ &\mathit{Load\ active\ power\ of\ base\ case} \end{aligned} \quad (3)$$

The loads are usually PQ bus in power flow case, so the load is set with the constant power factor in 24 hours. Based on the constant ratio of reactive and active power in the base case, the reactive power of individual load in each hour is as follows:

$$\begin{aligned} &\mathit{Load\ reactive\ power\ of\ i^{th}\ hour} \\ &= \mathit{Ratio\ between\ reactive\ and\ active\ power\ of\ base\ case} \cdot \\ &\mathit{New\ load\ active\ power\ of\ i^{th}\ hour} \end{aligned} \quad (4)$$

After the replacement, there are two types of generators in this study: 1. Hydro and nuclear with a constant active power in 24 hours; 2. The combination of PV, wind, and battery with varying active power in 24 hours.

In the power flow cases, each hydro and nuclear generator has the same output, so no need to change their value.

For the combination unit of PV, wind, and battery, the process of obtaining active power is similar to that of load. Using the following equation, one could have the unit active power of individual unit in each hour.

$$\begin{aligned} &\mathit{Renewable\ unit\ active\ power\ of\ i^{th}\ hour} \\ &= \frac{\mathit{Total\ load\ power\ of\ i^{th}\ hour}}{\mathit{Total\ load\ power\ of\ base\ case}} \cdot \\ &\mathit{Load\ active\ power\ of\ base\ case} \end{aligned} \quad (5)$$

The renewable units are steam and gas generators, which are PV bus in the base case, so there is no need to further assign the reactive power value for these unit in each hour. The voltage values of each renewable unit are the same as those in base cases.

Based on the calculated values above, PSS/E python API is further used to read the base power flow case, change each load and renewable unit value. Then, the initial 24-hour power flows cases are developed. Newton-Raphson power flow algorithm is used to solve the power flows results. All cases have convergent results in this paper, but one must pay attention to the transmission line loss. When the DC dispatches are developed before AC power flow calculation, the transmission line losses are neglected. However, in AC power flow calculation, the transmission line losses result in the significant change of active power at the slack generator. It happens that the slack bus in this synthetic ERCOT system is the nuclear plant, whose active power is desired to be constant in 24 hours. Thus, the slack generator is reset to its initial value, and its relative active power deviation is distributed and added to the dispatch of the renewable generators. Then the power flow is solved again. This process is iterated multiple times to ensure the slack generator has a similar output as the desired value. Fig. 9 shows the 24-hour final active power of the slack bus after the tuning. It can be seen the final active power of the slack bus keeps relatively constant. Finally, 24-hour power flows cases are developed.

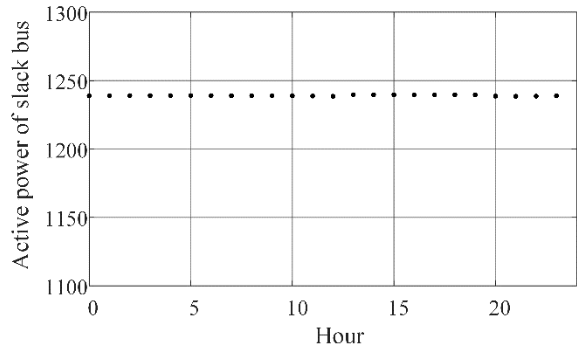

Fig. 9. 24-hour active power of slack bus by AC power flow calculation.

Based on the developed 24-hour power flow cases, many insightful results can be obtained. Fig. 10 shows the 24-hour voltage of a specified load bus. Clearly, the voltage around 17th hour is lower than those in other hours. If further checking the dispatches in Fig. 8, we could find that 17th hour is the peak-load hour, which could be the reason for the low voltage for load bus #7229.

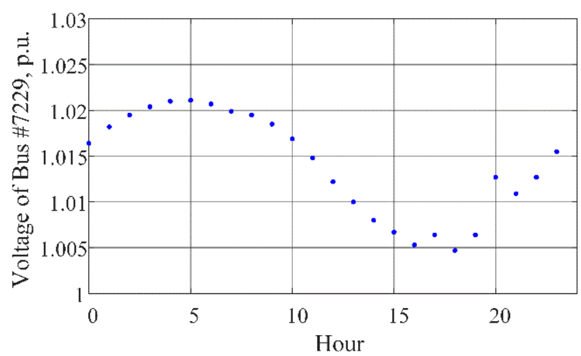

Fig. 10. 24-hour voltage of a specified load bus by AC power flow calculation.

V. Necessary Battery Capacity and Initial SoC

Besides the power flow development in this paper, a practical way to estimate the necessary battery capacity and initial SoC is also proposed. Based on the intraday dispatches in the previous sections, the battery should satisfy the following requirements: 1) the ability to absorb the maximum continuous surplus energy; 2) the initial energy larger than the maximum continuous power deficit.

The battery charging energy is determined by the gap between power generation and the load, which is calculated as

$$P_{battery,i} = P_{nuclear,i} + P_{hydro,i} + P_{PV,i} + P_{wind,i} - P_{load,i}, i = 0,1,...,23 \quad (6)$$

where $P_{device,i}$ is the power of the device at time i, $device$ = [*battery, nuclear, hydro, PV, wind, load*].

As shown in Fig. 11, the area below the x-axis (x-axis: where the battery charging power is 0) means discharging (area A1 and A3), whereas the area above x-axis means charging (area A2).

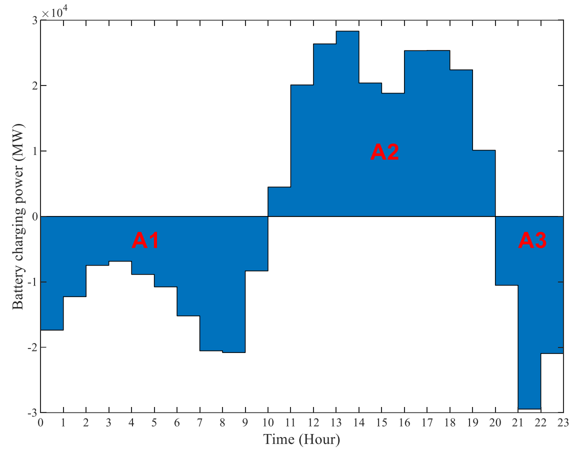

Fig. 11. Battery charging power.

Further, the net exchange energy of the battery is the cumulative of the battery charging power, as follows:

$$E_{battery,exc,i} = \sum_{k=0}^{i} P_{battery,i} \cdot 1h,\ i = 0,1,...,23 \quad (7)$$

where $E_{battery,exc,i}$ is the exchange energy of the battery at time i.

The battery capacity should satisfy the absorption of the surplus energy, as shown in Fig. 12, the gap between the highest and the lowest point of the net exchange energy decides the minimum battery size:

$$S_{battery} \geq E_{battery,exc,\max} - E_{battery,exc,\min} \quad (8)$$

where $S_{battery}$ is the capacity of the battery.

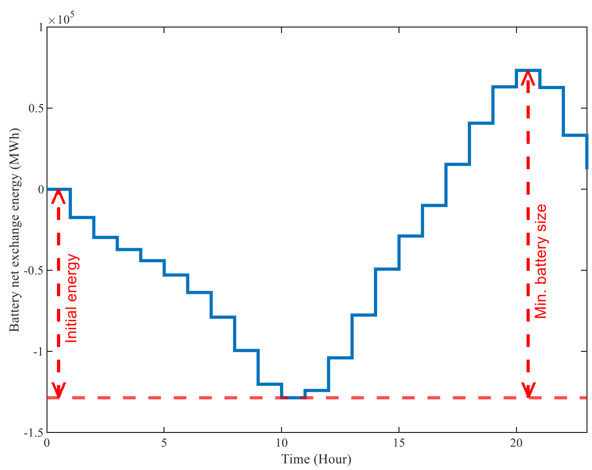

Fig. 12. Battery net exchange energy

The battery initial energy should satisfy the power deficit, where the maximum continuous discharging energy is covered:

$$E_{battery,0} = -E_{battery,exc,\min} \quad (9)$$

where $E_{battery,0}$ is the initial energy of the battery.

As shown in Figure 12, the lowest point determines the initial energy. Once the battery capacity is determined, the initial SoC can be further determined:

$$SoC_0 = E_{battery,0} / S_{battery} \quad (10)$$

Using the developed dispatches, the maximum and minimum battery exchange energy can be obtained as 73.3 GWh and -128.5 GWh, respectively. Then, the minimum battery size is determined as 201.8(=73.3+128.5) GWh. Finally, the initial SoC can be determined by the battery size and the initial energy, which is 63.68%. It should be noted that, the initial SoC will decrease if the battery size is designed larger for the security margin.

VI. CONCLUSIONS

In this paper, 24-hour power flow cases are developed for a carbon-free synthetic ERCOT model. Based on the developed dispatches, the estimation of necessary battery capacity and SoC is also proposed. The developed cases have several advantages: 1. The base model is a large-level national system; 2. The load, PV, and wind profiles used are actual data from EIA; 3. There is no transmission line expand issue in these developed cases; 4. The battery could achieve the energy balance in a 24-hour cycle. Besides of the development of power flow cases, battery sizing method for a notional carbon-free power grid is also proposed.

This paper offer a implementable way to develop the carbon-free grid power flow cases. In future study, when expansion information of the load, renewable and transmission line are available, the development of power flow cases is better to include.

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