Transmission Impedance Control Impacts on Carbon Emissions and Renewable Energy Curtailment

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Abstract

Increased levels of renewable energy penetration have created new congestion patterns in recent years. Since the grid is not designed for the new patterns, the operators may need to curtail renewable energy to maintain transmission flows within acceptable limits. Transmission line impedance control, using flexible ac transmission system (FACTS) devices, has been proposed as an approach to relieve congestion in transmission systems and enhance renewable energy utilization. In this paper, we conduct a comprehensive study to provide insights on FACTS implementation's impact on renewable energy integration and carbon emission reduction. The study considers variations in renewable energy penetration level, system loading patterns, location of renewable generation, and location of FACTS devices. Furthermore, generation mix data from prominent regional transmission organizations (RTO) are used to achieve more realistic results. Simulations studies are carried out on a modified RTS-96 system with a two-stage stochastic unit commitment model. The results show that, even though impedance control is effective in cost reduction, it has limitations in facilitating renewable energy integration in systems with prominent cheap fossil fuel power plants.

Keywords: Carbon emissions, flexible ac transmission systems (FACTS), power flow control, renewable energy, solar energy, stochastic unit commitment, weather variability, wind energy

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Nomenclature

Indices

g	Generator
k	Piece-wise linear cost function segment
l	Transmission line
n	Bus
r	Renewable energy resource
s	Scenario
t	Time

Parameters

π_{st}	Scenario s probability at time t
b	Transmission line susceptance
b^{max}	Maximum susceptance for transmission line equipped with FACTS
b^{min}	Minimum susceptance for transmission line equipped with FACTS
c_g^{nl}	Generator no-load cost
c_g^{sd}	Generator shut-down cost
c_g^{su}	Generator start-up cost
c_g^{UE}	Energy deployment cost
c_r^{RC}	Renewable energy curtailment cost
c_{gk}^{seg}	Piece-wise linear generation cost
DT_g	Generator minimum down time
G	Total number of generators
K	Total number of segments in piece-wise linear cost function
L	Total number of transmission lines
P_{nt}^D	Real power demand at bus n
P_{rts}^R	Renewable energy generation
P_g^{max}	Generator upper generation limit
P_g^{min}	Generator lower generation limit
PL^{max}	Transmission line thermal rating
R	Total number of renewable energy resources
RD_g	Generator per-minute ramp-down rate
RU_g	Generator per-minute ramp-up rate
S	Total number of scenarios

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T	Time horizon
UT_g	Generator minimum up time

Sets

NG_n	Set of generators located at bus n
NL_n^+	Set of transmission lines flowing into bus n
NL_n^-	Set of transmission lines flowing from bus n
NR_n	Set of renewable energy resources located at bus n

Variables

θ^R	Voltage angle on receiving bus
θ^S	Voltage angle on sending bus
F	Transmission line flow direction
P_{gtk}^{seg}	Real power generated in the kth segment of generator
P_{gts}^{rd}	Real power ramp-down
P_{gts}^{ru}	Real power ramp-up
P_{gt}	Generator real power generation
P_{rts}^{RC}	renewable energy curtailment
PL	Real power flow through line
u_{gt}	Generator up/down status
v_{gt}	Generator start-up variable
w_{gt}	Generator shut-down variable
x_l^f	FACTS allocation variable

1. Introduction

To battle climate change, renewable energy resources have been deployed as cost-effective, emission-free alternatives to fossil fuel power plants. The United States, for instance, has increased its renewable energy supply by 50% during the past decade [1] and has an ambitious goal of reaching a carbon-free grid by 2035 [2]. This is an initial step towards a carbon-free US economy by 2050. With the same approach, Canadian government has developed the RETscreen software for evaluating the financial viability and carbon emission reduction benefits of various energy projects with the main concern of environmental impacts [3]. In contrast with conventional fossil-fueled thermal units, renewable energy resources are intermittent and more or less not dispatchable. Transmission networks, conventionally designed to handle dispatchable generation, have faced difficulties handling the variability of renewable energy generation. This has led to renewable energy curtailment due to transmission constraints. U.S. balancing authorities experienced an average of 1% to 4% of wind curtailment between 2007 and 2013 [4]. Major Independent System Operators (ISO) has adopted various approaches to address this issue. The California ISO (CAISO), with 7,800 MW of wind and 15,000 MW of solar generation capacity installed as of 2022, has experienced large amounts of renewable energy curtailment, mainly due to congestion [5]. The Electric Reliability Council of Texas (ERCOT), with a 25% share of wind generation as of 2021, experienced an average of 8% of wind curtailment, which peaked at 17% in 2009 [4, 6]. The curtailment was reduced to about 1.6% in 2013 after ERCOT carried out transmission expansion. It is important to note that transmission expansion is a rather costly solution for the congestion caused by renewable energy resources. The Midcontinent Independent System Operator (MISO), with 28.9% of wind energy penetration, adopted the Dispatchable Intermittent Resource protocol in 2011 to address the recurring wind curtailment problem [7, 8]. Pennsylvania-New Jersey-Maryland (PJM) interconnection experienced about 80,000 MWh of wind curtailment with the lost opportunity cost of $3 million during September 2012 [4]. To increase efficiency and reduce the curtailment, PJM changed its curtailment signaling and compensation process in 2013 and has lowered maximum wind curtailment from 8% in 2014 to less than 4% in 2019 [9].

Besides the abovementioned solutions, several other approaches have been suggested to reduce renewable energy curtailment in the literature. Energy storage has been proposed in [10], including battery storage [11], pumped hydro storage, and compressed air storage to manage load-generation balance and decrease renewable energy curtailment. While energy storage can potentially solve many of today's challenges, the high cost is still a major obstacle to its adoption. Demand response through flexible loads has been suggested as another approach to matching the demand with the generation, but this method is limited by the scarcity of flexible loads [12, 13, 14]. Since the main reason for renewable energy curtailment is transmission system congestion, an alternative approach is to enhance the transfer capability of the existing network by exploiting transmission flexibilities. Such flexibility can be offered by phase shifters [15], transmission switching [16, 17] or flexible ac transmission system (FACTS) devices [18, 19]. FACTS devices can control various properties of power systems, such as voltage phase and magnitude, shunt susceptance, or line impedance [20, 21]. Variable-impedance FACTS devices can be effectively utilized to control power flow. In [22], a stochastic unit commitment (SUC) model is proposed to optimally adjust FACTS set-points and thermal units' generation to minimize wind curtailment. References [23, 24] propose a framework to implement series FACTS devices in market environments to increase the transfer capability of the transmission system. The interdependence of variable-impedance FACTS devices and transmission switching in power flow control is shown in [25]. Although mathematical models have been presented in the literature for optimal adjustment of FACTS devices, their impact on cost savings, carbon emission, and renewable energy curtailment depends on several operational factors that have not been considered. In our recent study [26], as a preliminary analysis, we showed the impact of FACTS allocation on carbon emission and renewable energy curtailment. Considering the central role of grid-enhancing technologies in decarbonization, [26] conducted a study on the impact of FACTS device deployments and showed that FACTS could cause increased carbon emissions in some scenarios. However, a more comprehensive study with more scenarios involving realistic generation mix data is still in need.

This paper fills the research gaps by presenting a comprehensive study on the impact of variable-impedance power flow control on cost savings, carbon emission, and renewable energy curtailment under several realistic operational conditions, including spatial distribution of FACTS devices as well as renewable energy resources, representative load curves for daily and seasonal demand variations, generation mix from major ISO/RTOs including CAISO, MISO, ERCOT, ISO New England (ISO-NE), and PJM. We use a two-stage SUC model to study the impact of FACTS devices on power system operation under increased levels of renewable energy penetration. Simulation studies are carried out on the RTS-96 system. The results show that the proximity of FACTS devices to coal-fired units undermines the environmental merits of power flow control. The generation mix and ramping flexibility of generation units highly impact the effectiveness of FACTS implementation. Finally, the FACTS devices incur the highest cost saving during peak-demand days by relieving congestion in the network but can adversely increase carbon emissions by increasing coal-fired units. The rest of this paper is organized as follows. The rest of this paper is organized as follows. Section 2 details the variable-impedance FACTS modeling and the stochastic unit commitment model used in this paper to analyze the impact of power flow controllers on grid operation. Section 3 presents an overview of the current generation mix in major ISO/RTOs and its impact on FACTS operation. Section 4 implements the stochastic model presented in section 2 on the RTS-96 system under several realistic operational conditions, including FACTS and renewable farm locations, renewable penetration level, generation mix, and load curve. Finally, section 5 concludes the paper with a brief overview of the main remarks from the results and future work. Overall, the main contributions of this article can be summarized as follows:

- Development of an emission incorporated stochastic unit commitment model, to analyze the impacts of power flow controllers on carbon emission,
- Extensive analysis of carbon emission on real-life generation mix from major system operators in the United States,
- Pinpointing the adverse impact of FACTS power flow controller allocation close to coal units or congested renewable areas in carbon-intensive grid,
- Analysing the effectiveness of power flow controllers for alleviating renewable energy curtailment under a range of renewable energy penetration levels and identifying the critical point for grid expansion planning,
- Full study of various demand patterns and impact of FACTS devices in each case.

2. Methodology

In this section, we first introduce the methodology we have used to study the impact of FACTS devices on carbon emission under different conditions. For our study we use a two-stage SUC model with FACTS implementation, which is presented in the paper. The SUC formulation uses scenarios to represent possible realizations of renewable generation uncertainty, a widely adopted approach for uncertainty management. We first introduce the FACTS modeling applied in this paper before presenting the full problem formulation. Then, we implement the model of FACTS devices in the two-stage stochastic unit commitment model, later introduced in this section. Section 3 will introduce the specifications of various generation units and their carbon emission properties with a comprehensive study. Section 4 first feeds the base case model data into our stochastic optimization model and derives the base case results for generation cost, renewable energy curtailment and carbon emission. The section, then, studies the impact of renewable energy resources location and penetration level to address the conditions that power flow control can adversely impact carbon emissions and renewable energy curtailments. This analysis is followed by generation mix analysis for real-life generation mixes from six major ISO/RTOs in the United States. Finally, to study the impact of demand pattern, the operation of FACTS devices is scrutinized for different load curve patterns to derive the effect of ambient weather and consumer behaviour on operation of FACTS devices and carbon emission. Overall, the methodology used in this paper is summarized in Fig. 1.

In this study, we use FACTS devices that provide variable-impedance control, which can be implemented using several different FACTS technologies, including the thyristor-controlled series compensators (TCSC), static synchronous series compensators (SSSC), and the unified power flow controller (UPFC). The light-weight and compactly distributed or modular FACTS (D-FACTS or M-FACTS) devices, such as SmartValve$^{\text{TM}}$ [27] by Smart Wires Inc., have recently been introduced and implemented in the industry. In this paper, we use the FACTS modeling, where devices directly alter the reactance of transmission lines. This is suitable for prominent FACTS devices, such as TCSC, which have effectively controlled power flow and transmission system losses in the grid [28]. Moreover, [29, 30] proposed efficient linear models for integrating FACTS devices into grid optimization models. Note that different types of FACTS devices employ different technologies to alter the apparent impedance of transmission lines. SSSC and UPFC devices, for instance, use a voltage injection to effectively emulate a reactance change [31]. However, the effect is similar for different types of series FACTS devices. The results in this paper can be applied when other types of FACTS technologies are employed in the system.

Variable-impedance FACTS devices can adjust line susceptance within a range to increase the transfer capability. Therefore, the real power flow constraint can be written as follows for each line equipped with FACTS:

$$PL = b(\theta^R - \theta^S). \tag{1}$$

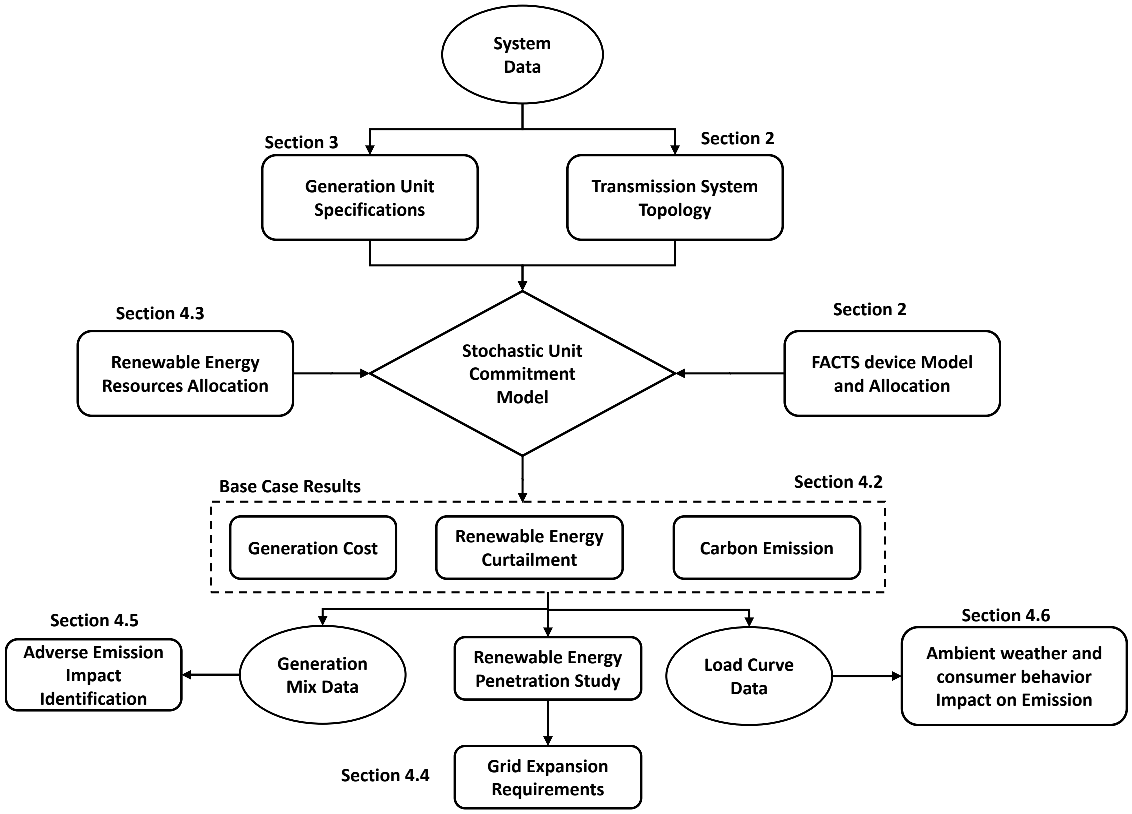

Figure 1: Methodology of Current Study

This equation show the DC equation of line flow PL obtained from multiplying bus angle θ difference by line susceptance b_l. It should be noted that the equation above is nonlinear since the previously constant line susceptance b is now treated as a variable with its limits of $b^{min} \leq b \leq b^{max}$. Based on the method proposed in [32], this equation can be rewritten into two linear constraints with $F (F \in \{0, 1\})$ representing the power flow direction:

$$b^{min}F(\theta^R - \theta^S) + b^{max}(1 - F)(\theta^R - \theta^S) \leq PL, \tag{2}$$

$$b^{max}F(\theta^R - \theta^S) + b^{min}(1 - F)(\theta^R - \theta^S) \geq PL. \tag{3}$$

By determining the value of flow direction F, the nonlinear equation (1) can be reformulated to either of linear equations (2) or (3) as they include the multiplication of a parameter (b^{min} or b^{max}) by the fixed value of F and the variable angle difference. The value of F can be fixed using the a base case solution with no FACTS implementation [18, 22].

Wind generation can be modeled by the wind turbine model described in [33, 34]. The wind energy is attained between cut-in and cut-out wind speeds and is proportional to the cubic wind speed. Solar generation depends on both intrinsic characteristics of photovoltaic (PV) panels, which are usually reported by current-voltage (I-V) and power-voltage (P-V) charts as well as extrinsic irradiation conditions [35]. Wind speed and solar radiation both change within continuous ranges, which creates infinite scenarios and makes it impractical to optimize the dispatchable generation and FACTS set points for the continuous uncertainty space. To overcome this challenge, a smaller number of scenarios are selected by choosing representative ranges for wind speed and solar radiation and creating discrete scenarios for solar and wind generation. Using scenarios for modeling uncertainty, the SUC with FACTS adjustment co-optimization model can be formulated as shown in (4a)-(4p). The following mathematical model is fed into PYOMO, a powerful mathematical modeling package provided in python programming language. This modeling environment can solve complex linear and nonlinear programming problem and is compatible with commercial solvers such as Gurobi and CPLEX.

$$\begin{aligned}
&minimize \sum_{g=1}^{G}\sum_{t=1}^{T}(c_g^{nl}u_{gt} + c_g^{su}v_{gt} + c_g^{sd}w_{gt}) \\
&+ \sum_{g=1}^{G}\sum_{t=1}^{T}\sum_{k=1}^{K} c_{gk}^{seg}P_{gtk}^{seg} + \sum_{g=1}^{G}\sum_{t=1}^{T}\sum_{s=1}^{S} \pi_{st}c_g^{UE}(P_{gts}^{ru} + P_{gts}^{rd}) \qquad (4a) \\
&+ \sum_{r=1}^{R}\sum_{t=1}^{T}\sum_{s=1}^{S} \pi_{st}c_r^{RC}P_{rts}^{RC}
\end{aligned}$$

$$P_{gt} = \sum_{k=1}^{K} P_{gtk}^{seg}, \qquad \forall g, t; \tag{4b}$$

$$P_{gt} + P_{gts}^{ru} - P_{gts}^{rd} \leq P_{g}^{max} u_{gt}, \qquad \forall g, t, s; \tag{4c}$$

$$P_{gt} + P_{gts}^{ru} - P_{gts}^{rd} \geq P_{g}^{min} u_{gt}, \qquad \forall g, t, s; \tag{4d}$$

$$v_{gt} - w_{gt} = u_{gt} - u_{gt-1}, \qquad \forall g, t; \tag{4e}$$

$$v_{gt} + w_{gt} \leq 1, \qquad \forall g, t; \tag{4f}$$

$$\sum_{\tau=t-UT_g-1}^{t} v_{g\tau} \leq u_{gt}, \qquad \forall g, t; \tag{4g}$$

$$\sum_{\tau=t-DT_g-1}^{t} w_{g\tau} \leq 1 - u_{gt}, \qquad \forall g, t; \tag{4h}$$

$$P_{gt} - P_{gt-1} \leq 60RU_g u_{gt-1} + 10RU v_{gt}, \quad \forall g, t \geq 2; \tag{4i}$$

$$P_{gt-1} - P_{gt} \leq 60RD_g u_{gt} + 10RD_g w_{gt}, \qquad \forall g, t \geq 2; \tag{4j}$$

$$0 \leq P_{gts}^{ru} \leq 10RU_g, \qquad \forall g, t, s; \tag{4k}$$

$$0 \leq P_{gts}^{rd} \leq 10RD_g, \qquad \forall g, t, s; \tag{4l}$$

$$-PL^{max} \leq PL \leq PL^{max}, \qquad \forall l, t, s; \tag{4m}$$

$$\begin{aligned} & x_l^f (F_l b_l^{min} + (1 - F_l) b_l^{max})(\theta_{lts}^S - \theta_{lts}^R) \\ & + ((1 - x_l^f) b_l (\theta_{lts}^S - \theta_{lts}^R) \leq PL_{lts}, \qquad \forall l, t, s; \end{aligned} \tag{4n}$$

$$\begin{aligned} & x_l^f (F_l b_l^{max} + (1 - F_l) b_l^{min})(\theta_{lts}^S - \theta_{lts}^R) \\ & + ((1 - x_l^f) b_l (\theta_{lts}^S - \theta_{lts}^R) \geq PL_{lts} \qquad \forall l, t, s \end{aligned} \tag{4o}$$

$$\begin{aligned} & \sum_{g \in NG_n} (P_{gt} + P_{gts}^{ru} - P_{gts}^{rd}) + \sum_{r \in NR_n} (P_{rts}^{R} - P_{rts}^{RC}) \\ & + \sum_{l \in NL_n^+} PL_{lts} - \sum_{l \in NL_n^-} PL_{lts} = P_{nt}^{D} \qquad \forall n, t, s \end{aligned} \tag{4p}$$

The model seeks to minimize the summation of total expected generation cost, start-up cost, and shut-down cost of generators (4a), while considering generator capacity constraints (4b)-(4d), start-up and shut-down constraints (4e)-(4h), and ramping constraints (4i)-(4l). The generation cost is determined based on generation unit fixed cost c^{nl} and variable costs c^{seg} and is usually a nonlinear curve. However, it is transformed to piece-wise linear cost model for different generation levels. The start-up cost c^{su} and shut-down c^{sd} represent the fuel and labor costs incurred by starting a unit during peak demand hours and shutting down afterwards. The energy deployment cost C^{UE} represents the cost of a generator to change its genration because of load or renewable generation forecast inaccuracies and needs to be considered in real-time for safe operation of the system. Finally, the renewable energy curtailment cost c^{RC} represents the cost of lost opportunity incurred by out of merit scheduling of generation units due to congestion in transmission system or contingencies. The constraint (4b) ensures that generators output P_{gt} equals the total generation on each segment of piec-wise linear model P_{gtk}^{seg}. Constraints (4c) and (4e) ensure that generator scheduled output P_{gt} and real-time ramping P^{ru}, P^{rd} do not exceed the generation unit's capacity limits. Equation (4e) determines the generation units start-up or shut-down status ($v_{g,t}, w_{g,t}$ based on generators operating mode u_{gt} at specific period and previous period. Equation (4f) ensures that the generator cannot simultaneously start up and shut down. Equations (4g) and (4h) impose the minimum up and down time limits (UT_g, DT_g) of the generator, which are required for reliable operation of generators based on their technology. Similarly equations (4i)-(4l) impose the 10-minute and 60-minute ramping limits (RU, RD) for each generator based on their ramping capabilities. Line maximum flow constraint is given in (4m), and the line flow equation in the presence of FACTS devices is presented in (4n)-(4o) with the linearized formulation proposed in equations (2) and (3). The nodal power balance equation is given in (4p), ensuring that energy consumption at each node is adequate for the demand at the same node. This model can be considered from two different viewpoints. Suppose x_l^f is taken as a decision variable. In that case, the model describes a FACTS allocation problem which is a mixed-integer non-linear program (MINLP) due to the existence of the products of two decision variables, which is extremely computationally expensive. One way to reduce the computational cost is to linearize the problem, using the big-M technique described for this problem in [18]. However, in this study, as we intend to evaluate the impact of FACTS device locations on dispatch outcomes, the FACTS devices are allocated to candidate lines chosen based on engineering judgment. Therefore, x_l^f is treated as a parameter, making the formulation a mixed-integer linear program (MILP) that can be solved reasonably with existing commercial optimization packages, such as CPLEX and Gurobi. These packages use many methods for solving MILP problems, including barrier, branch-and-bound, and interior point methods [36]. Beside these methods, efficient methods have been proposed for solving optimization problems in energy systems, including the Levenberg–Marquardt method (LM) combined with genetic algorithm proposed by [37] for parameter estimation in inverse fouling heat exchanger.

3. The Importance of Generation Mix on FACTS Implementation Study

Generation mix directly impacts the operation of the power grid as well as carbon emissions. Power flow control can impact the power grid differently based on the generation units' economic specifications, technical specifications, fuel type, and emission specifications. Especially in a congested network, the operation of FACTS devices may replace renewable generation with inexpensive yet carbon-intensive generation units. Therefore, sufficient knowledge of generation unit technical and environmental specifications is required to study FACTS impact on carbon emissions. Fig. 2 shows the current status of the generation mix for five major ISO/RTOs in the United States, excluding non-hydro renewable generation. This section briefly overviews current prevalent fuel types and their share of the generation mix in the ISO/RTOs.

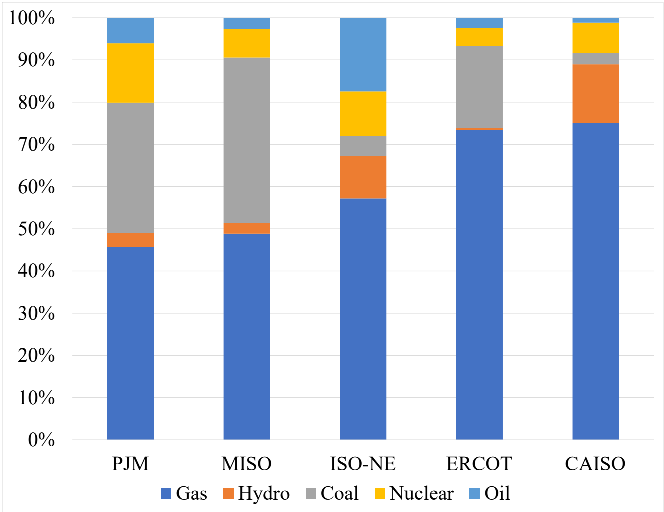

Figure 2: Dispatchable Generation Mix for Major ISOs in the U.S.

Coal is an inexpensive and abundant source of energy. Making 37% of the electricity generation, coal is the second largest source of energy in the United States and still the main source of CO_2 emissions in the power grid. Coal reserves are mainly available in four different types. The largest portion of coal resources is lignite, which has the lowest energy level. Subbituminous coal, with a higher level of stored energy, is the second prevalent type of coal. Bituminous, also known as soft coal, has the second thermal energy density in coal types. Finally, anthracite is the rarest type of coal, although it has the highest level of stored energy. Coal combustion produces other greenhouse gases such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) as well as CO_2. Furthermore, coal mining is a source of methane emission (CH_4). The coal industry has adopted several methods to reduce emissions from coal-fired electricity generation, including desulfurization and carbon capture equipment development [38].

Heavy oil fuel, with the smallest share in the generation mix, produces similar levels of greenhouse gases per unit of energy generation and is considered a polluting energy source. Roughly 70% of oil-fired generators were constructed before 1980. Oil-fired plants are generally committed during times of peak demand. These units have low capacity factors, mainly due to the high oil price. Since oil-fired generators are generally used to meet peak demand, they are designed to have low capacity factors and higher heat rates. Some plants can switch between oil and natural gas [39]. They burn natural gas to supply baseline demand and oil to meet peak demand. Natural gas has surpassed coal and is currently the leading generation source in the US. Natural gas-fired combined cycle plants are currently the most popular technology to supply base-load demand in the US. Other natural gas-fired plants, including combustion and steam turbines, are committed during higher demand periods. Natural gas emits less greenhouse gases than oil and coal and is a cleaner energy source, although it still produces similar levels of greenhouse gases. Natural gas-fired plants have experienced an upward trend during recent years as the capacity factor for gas-fired generation in the US has increased from 43% in 2011 to 56% in 2016 [40].

Hydropower, the largest renewable energy resource in the US until recent years, is surpassed by wind generation in 2019 [41]. In 2020, hydroelectricity comprised 6.6% of total electricity generation across the US and 31% of renewable energy generation [42]. Hydropower, unlike fossil fuels, is an emission-free and cheap energy source. However, hydropower expansion is limited by the availability of water. Conventional hydroelectric plants includes run-of-the-river systems, where the energy is supplied by the force of river's current, and reservoir systems, where the water is accumulated behind a dam and released through a turbine to generate electricity. Reservoir systems can be further upgraded to pumped-hydro storage that can pump water to a higher elevation during times of lower electricity price and release the power during peak load, when the electricity prices are high [43]. Unfortunately, geographical locations allowing pumped-hydro storage development are already used [44].

Nuclear power plants have generated around 20% of annual electricity consumption in the US since 1990 [45]. Nuclear power plants produce heat by nuclear fission to generate steam. The steam goes through a turbine and then cooled back into water in a cooling tower or the water is supplied from the ocean or river close to the facility. Like natural gas-fired plants, nuclear plants are used to supply baseline demand. Nuclear power plants produce no carbon emissions [46]. However, the nuclear waste produced in the electricity generation process in this type of plants is a major environmental concern. The radioactive radiation from the waste can remain dangerous for humans and the environment for thousands of years. Therefore, it needs to be disposed under special regulations [47].

Average operational generation cost and carbon emission for different types of plants is provided in Table 1, based on the data from Environmental Protection Agency's Emissions & Generation Resource Integrated Database (eGRID) [48, 49]. Using ISO/RTO's generation mix data, the results can more realistically reflect the impact of power flow control implementation on carbon emission and renewable generation curtailment.

Table 1: Average Carbon Emission and Generation Cost for Plant Types

	Emission Rate (lb/MWh)	Generation Cost ($/MWh)
Coal-fired	2027	22
Oil-fired	1671	121
Gas-fired	1169	14
Nuclear	0	2
Hydropower	0	0

4. Simulation Studies

To evaluate the impact of FACTS devices on generation cost, renewable energy curtailment, and carbon emission, the co-optimization SUC model described in (4a)-(4p) is implemented on a modified RTS-96 system with specifications presented in the following over a 24-hour time horizon. Renewable energy resources based on their type and location and the topology of the grid can create different congestion patterns and, therefore different cost savings by FACTS installation. To study the impacts of FACTS devices, simulations were carried out under a wide range of scenarios. In each part of the simulation studies, the two-stage SUC model is solved using CPLEX 20.1.

4.1. Test System Specifications

The studies are carried out on a modified single-area RTS-96 system with 24 buses [48]. 480 MW of load on buses 14, 15, 19, 20 ere shifted to bus 13 and then loads on every bus in the system is increased by 5% yielding a total electricity demand of 59.660 GWh daily, considering the load curve data. To create congestion, the ratings of lines A25-1 and A25-2 are reduced to 175 MW, and ratings of lines A21 and A22 are reduced to 220 MW. Three pairs of candidate buses (4,5) as representative for buses close to demand, (17,18) as buses close to low-cost energy resources and (3,24) as typical buses in the system are considered for renewable energy resources. Three lines for FACTS device allocation are considered based on engineering judgement. Equipping highly utilized lines, lines with large capacity and lines with large reactance with FACTS devices are shown in the literature to be most effective for congestion relief [22]. A21 and A25-1 lines are taken as highly utilized lines and A26 is considered as a large-capacity line for FACTS allocation.

To study the impact of FACTS based on integrating different renewable energy resources, two wind farms and two solar farms are considered for each pair of candidate locations for renewables. The wind farms have rated wind speed of 14 m/s, a cut-in wind speed of 4 m/s, and cut-out wind speed of 25 m/s. The hourly solar irradiation and wind speed historical data obtained from national renewable energy laboratory (NREL) [50, 51] are used to create hourly figures for wind and solar generation, respectively. TCSC is used in simulation studies for power flow control in transmission lines. We consider FACTS devices operating in capacitive and inductive modes with the maximum adjustment range of -80% to +40% of line reactance [52]. To study the impact of FACTS devices on carbon emission, the generation mix is created based on generator specifications available in RTS-96 data and eGRID emission data. The generation mix for RTS-96 system is shown in Fig.3, while Table 1 shows the emission data for each unit type.

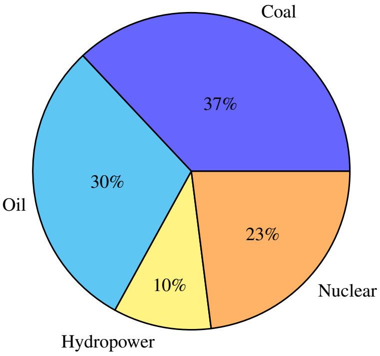

Figure 3: RTS-96 Generation mix

4.2. Base Case: Impacts of FACTS Implementation without Renewable Integration

Optimizing transmission impedance with variable-impedance FACTS devices saves cost and impacts carbon emissions, even without renewable energy integration. To evaluate the impact of FACTS on a system with conventional generation units, FACTS devices are installed in RTS-96 system without any renewable integration. The results shown in Table 2 provide a baseline for total generation cost and carbon emission. This baseline helps analyzing the impacts of FACTS setpoint adjustment on generation cost and carbon emissions under different renewable energy penetration levels and generation mixes in the later subsections. Maximum generation cost saving for a single FACTS device is achieved when installed on line 21, near inexpensive coal-fired units. Yet, it increases carbon emissions by replacing less polluting and more expensive units with coal-fired generation. This shows that adjusting FACTS setpoints with the mere objective of cost minimization (social welfare maximization) may lead to increased levels of carbon emissions in the power grid with considerable share of cheap yet carbon-intensive generation units, such as coal-fired power plants. The impact of FACTS devices on carbon emissions needs to be considered in FACTS allocation problem to make operation of FACTS devices environmental-friendly. The congestion rent is reduced in all cases.

4.3. Impacts of FACTS Implementation Under Varying Renewable Energy Locations

To study the impacts of FACTS devices on renewable energy integration, wind and solar farms with a capacity of 400 MW were located on different buses with 4891.71 MWh total daily solar generation and 6412.42 MWh total daily wind generation, using solar and wind scenarios obtained from historical

Table 2: Simulation Results for RTS-96 Without Renewable Energy Resources

Number of FACTS	FACTS Location (Line)	Total Generation Cost(M$)	Congestion Rent (M$)	Carbon Emission (Mlb)
0	N/A	1.988	0.248	66.551
1	21	1.714	0.195	67.351
2	25,26	1.885	0.247	63.662
3	21,25,26	1.659	0.186	64.398

data. Twenty-four simulations were carried out, with a simulation for each location of FACTS implementation and wind and solar farm siting. generation cost, carbon emission and curtailment level for wind and solar integration are shown in Tables 3 and 4, respectively. Implementing power flow control when wind and solar farms are located at (3,24) increases wind curtailment by 259.12 MWh and solar curtailment by 262.85 MWh. This is because the objective is to minimize cost. In this case, it is cheaper to dispatch coal units than to utilize zero marginal cost renewable generation due to the congestion in the network. Therefore, it is important to note that FACTS devices may increase renewable energy curtailment in networks with existing inexpensive generation mix. However, when wind and solar farms are located in congested areas, such as the proximity of load centers (4,5) or inexpensive generation units (17,18), renewable energy curtailment decreases with the power flow control. When wind and solar farms are near cheap energy resources, implementing FACTS in proximity of coal-fired units can increase curtailment, as shown for wind units in Table 3.

Table 3: Simulation Results for RTS-96 With Wind Integration

Wind Farm Location (Bus)	Number of FACTS	FACTS Location (Line)	Total Generation Cost(M$)	Carbon Emission (Mlb)	Wind Curtailment (MWh)
3,24	0	N/A	1.613	54.549	1390.43
	1	21	1.401	55.798	1560.95
	2	25,26	1.536	52.347	1527.21
	3	21,25,26	1.332	53.208	1649.85
4,5	0	N/A	1.525	54.391	447.45
	1	21	1.327	55.018	366.81
	2	25,26	1.447	51.576	454.07
	3	21,25,26	1.267	52.278	364.65
17,18	0	N/A	1.885	62.946	600.49
	1	21	1.645	64.170	627.26
	2	25,26	1.797	60.819	452.96
	3	21,25,26	1.556	61.193	452.96

Table 4: Simulation Results for RTS-96 With Solar Integration

Solar Farm Location (Bus)	Number of FACTS	FACTS Location (Line)	Total Generation Cost(M$)	Carbon Emission (Mlb)	Solar Curtailment (MWh)
3,24	0	N/A	1.697	59.463	1434.28
	1	21	1.453	60.677	1632.01
	2	25,26	1.614	56.970	1460.31
	3	21,25,26	1.396	58.216	1697.13
4,5	0	N/A	1.594	58.667	512.59
	1	21	1.384	59.297	508.03
	2	25,26	1.508	55.471	449.94
	3	21,25,26	1.311	56.397	453.73
17,18	0	N/A	1.914	64.262	229.47
	1	21	1.651	65.329	210.80
	2	25,26	1.826	61.454	383.44
	3	21,25,26	1.579	62.396	383.44

4.4. Impacts of FACTS Implementation Under Varying Renewable Energy Penetration Levels

As discussed in section 1, one of the main purposes of transmission line impedance control is to provide flexibility in the transmission system for increased levels of renewable energy penetration. Therefore, in this section, we study the impact of FACTS devices on different levels of renewable energy penetration. To simulate different penetration levels of renewable energy resources, wind and solar units are distributed over all candidate buses with equal distribution of wind and solar capacity on each bus. Then, the capacities of wind and solar units are increased in increments of 100 MW each. For each level of renewable capacity increment, the renewable penetration level is represented as the total capacity of variable generation (wind and solar) divided by the total generation capacity. Fig. 4 shows the total generation cost concerning renewable energy penetration for each allocation of FACTS devices. The maximum cost saving incurred by FACTS implementation declines from $0.33 M to $0.23 M as the renewable energy penetration approaches 50%. This shows that although FACTS devices lead to cost savings by alleviating congestion in the network, transmission expansion is also required for higher penetration levels (above 50%). This decline can also be observed in FACTS device impact on emission reduction as shown in Fig. 5. The maximum reduction in carbon emissions drops from 2.6 Mlb at 0% renewable penetration to 2.3 Mlb at 50% penetration level. Finally, Fig. 6 shows renewable energy curtailment for each penetration level. For penetration levels below 30%, FACTS adjustment helps reduce curtailment by relieving congestion in the network. However, as renewable energy penetration surpasses 30%, FACTS devices adversely increase renewable energy curtailment. This is due to the feature illustrated in the previous subsection. With increased levels of renewable energy penetration, dispatching cheap fossil fuel plants may become more economical than utilizing zero marginal cost RERs contributing to expensive transmission constraints. With other inexpensive generation resources, the optimal solution curtails a part of renewable generation to reduce congestion and total generation cost in the network. This further underlines the necessity of transmission expansion for high renewable penetration levels. All figures 3, 4 and five indicate the incremental benefit of renewable energy integration, including economic cost saving, carbon emission reduction and renewable energy utilization drop for penetration levels above 38% even with flexibility procured by FACTS devices. This saturation state is caused by lack of transmission capacity, and grid expansion is critical.

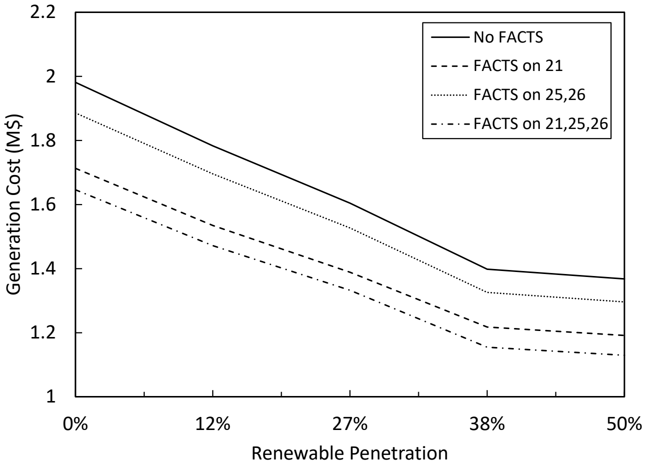

Figure 4: Cost Saving for Renewable Energy Penetration Levels

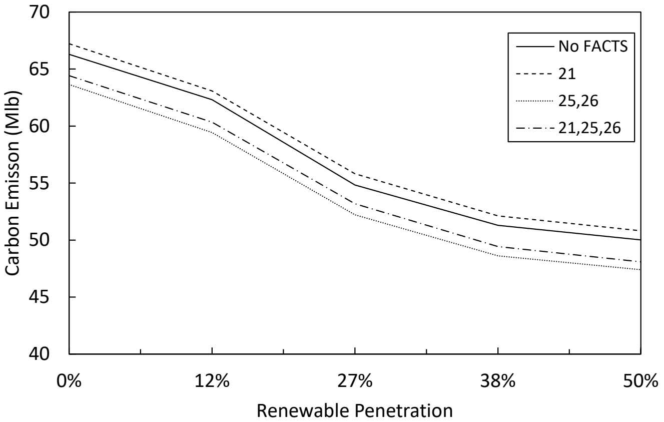

Figure 5: Emission Reduction for Renewable Energy Penetration Levels

4.5. *Impact of FACTS Implementation with Different ISO Generation Mixes*

In section 3, we discussed the influence of the generation mix on power flow control impacts and presented an overview of the current generation status for major balancing authorities in the U.S. In this subsection, we illustrate this impact by implementing the generation mix for six major ISOs shown in Fig. 2 on the RTS network with 50% penetration of wind and solar energy and evaluate the benefits of impedance control based on cost savings, carbon emission reductions, and renewable energy curtailment reductions. This penetration level represents the increased renewable energy integration goals envisioned in [2, 53]. Fig. 7 shows the impact of power flow control on generation cost for major ISOs. ISO-NE shows the highest level of cost savings from impedance control (6.8% reduction in generation cost). This is because ISO-NE incorporates the largest share of expensive oil-fired units (17%), and by relieving congestion, these units can be replaced by cheap renewable or gas-fired units. Fig. 8 shows carbon emissions for each ISO with power flow control. The emission reduction achieved by FACTS devices is small for high levels of renewable energy penetration, especially in ISOs such as MISO and ERCOT, where there is not enough flexibility in the generation mix to handle the variability of renewable generation. Still, for PJM, a maximum emission reduction of 1.25 Mlb (4%) can be achieved when FACTS devices are allocated optimally. The impact of FACTS on renewable energy curtailment is also small due to the lack of flexibility on the generation side, which results in renewable energy spillage. Similarly, FACTS devices are most effective in reducing renewable energy curtailment for PJM. This shows the importance of generation-side flexibility for better utilizing flexible transmission technologies. It should be noted that the influence of generation mix can be better studied with the transmission system proprietary data for each ISO. However, the impact of the generation mix shown in this section provides a baseline for more detailed grid studies.

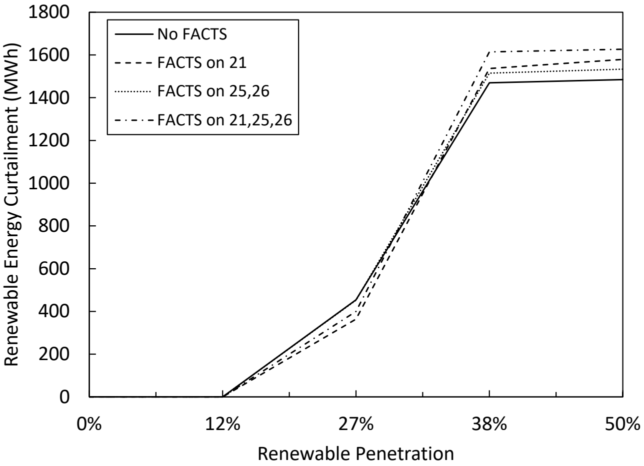

Figure 6: Renewable Energy Curtailment for Renewable Energy Penetration Levels

4.6. *Impacts of FACTS Implementation Under Varying Load Levels*

With increased levels of distributed renewable energy integration during the past decade, the net demand curve has become more weather-driven, and meteorological variations' im-

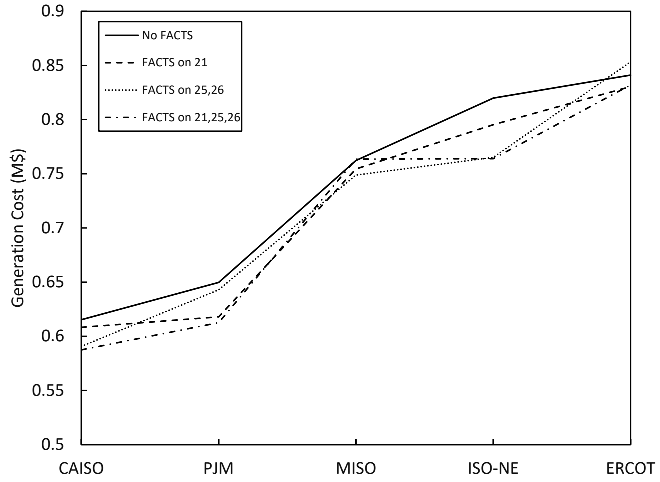

Figure 7: Generation Cost for Major ISOs Equipped with Impedance Control

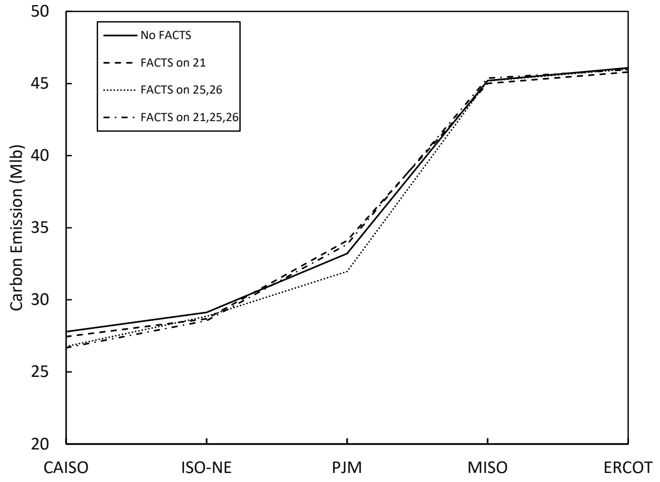

Figure 8: Carbon Emission for Major ISOs Equipped with Impedance Control

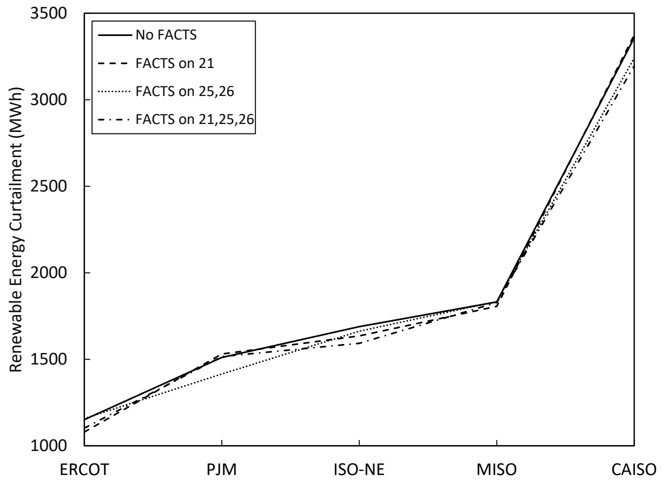

Figure 9: Renewable Energy Curtailment for Major ISOs Equipped with Impedance Cotrol

pact on the net load can be seen more distinctively than before [54]. Different load levels and peak hours create different congestion patterns, thus affecting the impacts of impedance control. To study the impacts of impedance control on cost saving, carbon emissions, and renewable energy curtailment under different load curves, 100 MW wind and solar units are placed at each candidate bus for renewables. Six representative load curves are considered for weekdays and weekends during mild, cold, and hot seasons to illustrate better load variations with seasonal changes based on the data from [55] and scaled to the RTS-96 system. Fig. 10 shows load variations for the six representative days. The distinct difference between weekend and weekday demand and the number of peak hours during hot and cold seasons are used to better study the effectiveness of impedance control on reducing generation cost, carbon emissions and renewable energy curtailment. The impact of impedance control on generation cost is shown in Fig. 11. The highest cost saving by impedance control is achieved during hot weekdays ($0.17 M) with the highest congestion pattern due to high demand levels and higher concentration of peaking hours. However, the largest reduction in emissions is not necessarily achieved during the peak of demand. With the congestion relieved, cheaper generating units with higher emission rates, such as coal-fired units, generate more power. Fig. 12 shows that the highest emission reduction by impedance control occurs during hot weekend days. Fig. 13 shows that the highest level of renewable energy curtailment happens during mild weekends when the electricity demand is at its lowest level. FACTS implementation helps reduce renewable energy curtailment by up to 3.77% (204 MWh out 5,410 MWh) by enhancing transfer capability.

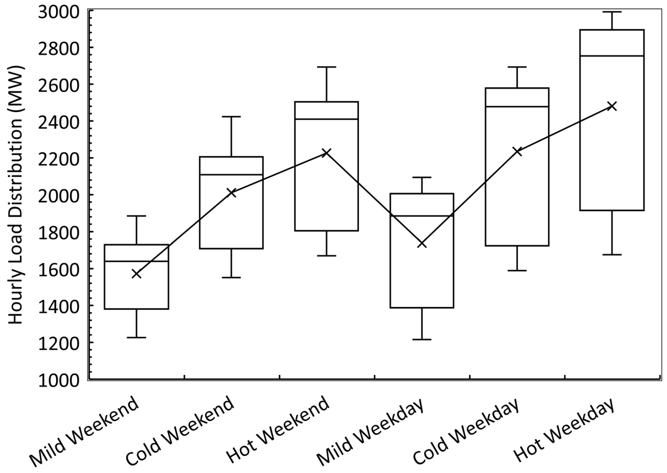

Figure 10: Hourly Demand Distribution For Representative Days

5. Conclusion

Implementing variable impedance FACTS devices are regarded as an effective approach for reducing the congestion in the power grid and improving the integration of renewable energy. However, various factors affect FACTS technology's effectiveness, which lead to different operation conditions. A

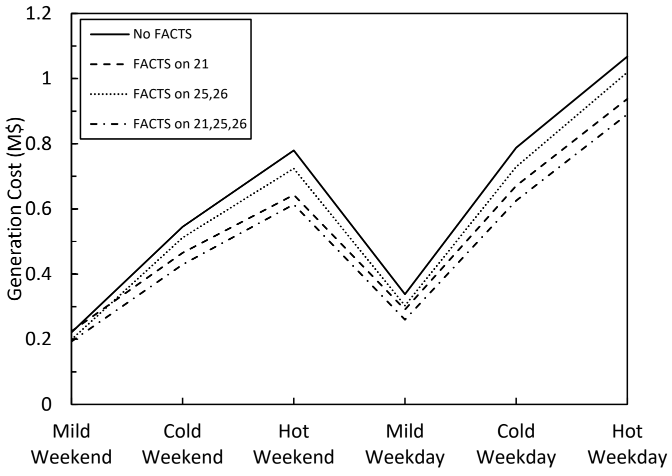

Figure 11: Generation Cost for Representative Days

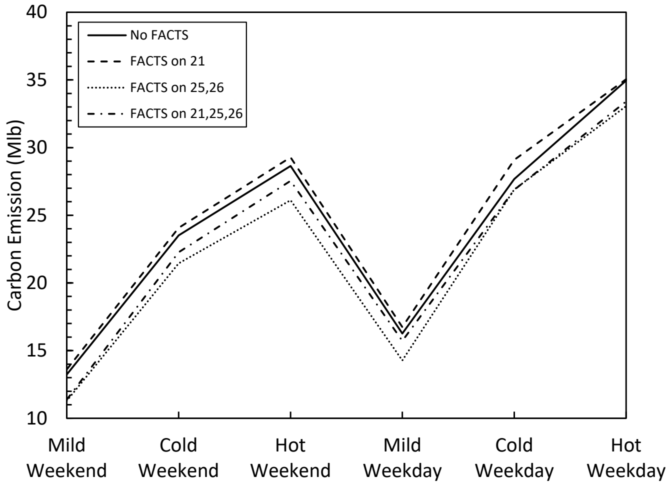

Figure 12: Carbon Emission for Representative Days

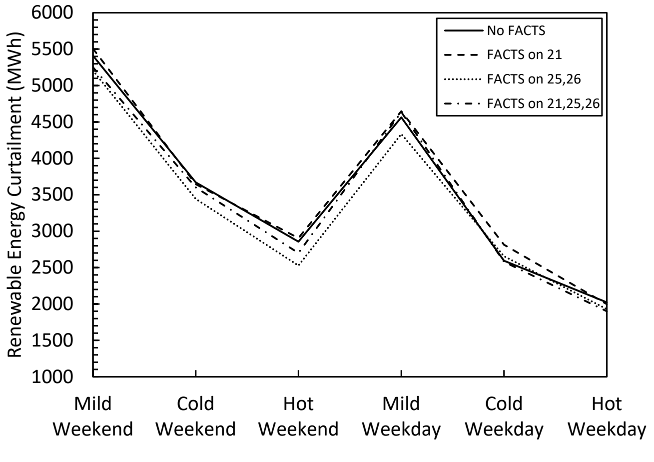

Figure 13: Renewable Energy Curtailment for Representative Days

comprehensive study was carried out in this paper to analyze the impacts of FACTS implementation with a two-stage SUC model. The key findings of this study are presented as follows:

- The location of FACTS installation near inexpensive carbon-intensive units such as coal-fired units may increase carbon emission and undermine the expected environmental benefits of power flow control.
- In some cases, renewable energy curtailment may increase for wind and solar units close to cheap fossil-fired units (gas or coal). In such cases, the renewable energy generation is often on a bus, contributing to expensive transmission constraints. In contrast, the fossil fuel plant either does the opposite (relieves the constraint) or has a much less weight in the constraint.
- For high levels of renewable energy penetration (above 50%), cost saving and emission reduction by FACTS devices declines and renewable energy curtailment increases. This shows that transmission expansion is required alongside topology control for FACTS implementation to be effective.
- ISO/RTO's generation mix highly influences the effectiveness of power flow control. This shows that generation unit analysis is required for transmission system upgrades.
- Weather-driven properties of load can change congestion patterns and, thus, influence the savings obtained from FACTS devices. The highest cost saving and emission level is achieved during hot seasons when the highest congestion level is achieved.

Future work will include co-optimizing FACTS implementation with transmission planning. In addition, studies on carbon-emission reduction policies that help harness the potential environmental benefits of power flow control will be beneficial.

6. Acknowledgements

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References

[1] Renewable and alternative fuels (2018).
URL `https://www.eia.gov/renewable/`

[2] D. Cusick, Biden's infrastructure plan would make electricity carbon-free by 2035, Scientific American (2021). doi:10.1038/d41586-019-02637-4.

[3] A. B. Owolabi, B. E. K. Nsafon, J. W. Roh, D. Suh, J.-S. Huh, Validating the techno-economic and environmental sustainability of solar pv technology in nigeria using retscreen experts to assess its viability, Sustainable Energy Technologies and Assessments 36 (2019) 100542.

[4] L. Bird, J. Cochran, X. Wang, Wind and solar energy curtailment: Experience and practices in the united states (2014).
URL `https://www.nrel.gov/docs/fy14osti/60983.pdf`

[5] Renewables and emissions reports (2022).
URL `http://www.caiso.com/market/Pages/ReportsBulletins`

[6] Ercot grid information (2022).
URL `https://www.ercot.com/gridinfo`

[7] M. I. S. O. (MISO), Real-time displays.
URL `https://bit.ly/3kg8bbn`

[8] J. S. John, Renewables curtailment in california and the midwest: What can we learn from grid operators' reports? (2016).
URL `https://bit.ly/3r1XrLl`

[9] PJM Interconnection LLC, Interregional planning stakeholder meetings and workshops.
URL `https://bit.ly/3wjM45V`

[10] K. Knezović, A. Marinakis, C. Y. Evrenosoglu, A. Oudalov, Role of grid and bulk storage in the integration of variable renewable energy resources: Framework for optimal operation-driven multi-period infrastructure planning, Energy 226 (2021) 120378.

[11] M. Salehi, M. Shahabadini, H. Iman-Eini, M. Liserre, Predictive control of grid-connected modified-chb with reserve batteries in photovoltaic application under asymmetric operating condition, IEEE Transactions on Industrial Electronics 69 (9) (2021) 9019–9028.

[12] M. V. Gasca, F. Ibanez, D. Pozo, Flexibility quantification of thermostatically controlled loads for demand response applications, Electric Power Systems Research 202 (2022) 107592.

[13] A. P. Sirat, H. Mehdipourpicha, N. Zendehdel, H. Mozafari, Sizing and allocation of distributed energy resources for loss reduction using heuristic algorithms, in: 2020 IEEE power and energy conference at Illinois (PECI), IEEE, 2020, pp. 1–6.

[14] F. Nematkhah, S. Bahrami, F. Aminifar, J. P. Catalão, Exploiting the potentials of hvac systems in transactive energy markets, IEEE Transactions on Smart Grid 12 (5) (2021) 4039–4048.

[15] J. A. Momoh, J. Z. Zhu, G. D. Boswell, S. Hoffman, Power system security enhancement by opf with phase shifter, IEEE transactions on power systems 16 (2) (2001) 287–293.

[16] S.-Y. Chen, C.-H. Wu, Y.-H. Hung, C.-T. Chung, Optimal strategies of energy management integrated with transmission control for a hybrid electric vehicle using dynamic particle swarm optimization, Energy 160 (2018) 154–170.

[17] M. Jabarnejad, Approximate optimal transmission switching, Electric Power Systems Research 161 (2018) 1–7.

[18] M. Sahraei-Ardakani, K. W. Hedman, A fast lp approach for enhanced utilization of variable impedance based facts devices, IEEE Transactions on Power Systems 31 (3) (2015) 2204–2213.

[19] M. Sahraei-Ardakani, K. W. Hedman, Day-ahead corrective adjustment of facts reactance: A linear programming approach, IEEE Transactions on Power Systems 31 (4) (2015) 2867–2875.

[20] S. Shakeri, M. Naghizadeh, S. Esmaeili, Identifying the voltage sags vulnerability area with considering facts devices, in: 2020 28th Iranian Conference on Electrical Engineering (ICEE), IEEE, 2020, pp. 1–5.

[21] M. Salehi, M. Khodabandeh, M. Amirabadi, Zeta-based ac-link universal converter, in: 2022 IEEE Energy Conversion Congress and Exposition (ECCE), IEEE, 2022, pp. 1–7.

[22] Y. Sang, M. Sahraei-Ardakani, M. Parvania, Stochastic transmission impedance control for enhanced wind energy integration, IEEE Transactions on Sustainable Energy 9 (3) (2017) 1108–1117.

[23] M. Sahraei-Ardakani, S. A. Blumsack, Transfer capability improvement through market-based operation of series facts devices, IEEE Transactions on Power Systems 31 (5) (2015) 3702–3714.

[24] M. Sahraei-Ardakani, Merchant power flow controllers, Energy Economics 74 (2018) 878–885.

[25] Y. Sang, M. Sahraei-Ardakani, The interdependence between transmission switching and variable-impedance series facts devices, IEEE Transactions on Power Systems 33 (3) (2017) 2792–2803.

[26] O. Mirzapour, M. Sahraei-Ardakani, Environmental impacts of power flow control with variable-impedance facts, in: 2020 52nd North American Power Symposium (NAPS), 2021, pp. 1–6. doi:10.1109/NAPS50074.2021.9449793.

[27] Smart Wires Inc., SmartValve$^{\text{TM}}$, accessed: 2022-07-10 (2022).
URL `https://www.smartwires.com/smartvalve/`

[28] M. Abdel-Moamen, N. P. Padhy, Power flow control and transmission loss minimization model with tcsc for practical power networks, in: 2003 IEEE Power Engineering Society General Meeting (IEEE Cat. No. 03CH37491), Vol. 2, IEEE, 2003, pp. 880–884.

[29] M. Sahraei-Ardakani, K. W. Hedman, Computationally efficient adjustment of facts set points in dc optimal power flow with shift factor structure, IEEE Transactions on Power Systems 32 (3) (2016) 1733–1740.

[30] Y. Sang, M. Sahraei-Ardakani, Effective power flow control via distributed facts considering future uncertainties, Electric Power Systems Research 168 (2019) 127–136.

[31] X. Rui, M. Sahraei-Ardakani, T. R. Nudell, Linear modelling of series facts devices in power system operation models, IET Generation, Transmission & Distribution 16 (6) (2022) 1047–1063.

[32] M. Sahraei-Ardakani, K. W. Hedman, A fast lp approach for enhanced utilization of variable impedance based FACTS devices, IEEE Transactions on Power Systems 31 (3) (2016) 2204–2213. doi:10.1109/TPWRS.2015.2447453.

[33] M. Mehrjoo, M. J. Jozani, M. Pawlak, Toward hybrid approaches for wind turbine power curve modeling with balanced loss functions and local weighting schemes, Energy 218 (2021) 119478.

[34] H. M. Al-Masri, A. A. Almehizia, M. Ehsani, Accurate wind turbine annual energy computation by advanced modeling, IEEE Transactions on Industry Applications 53 (3) (2017) 1761–1768.

[35] O. Mirzapour, S. K. Arpanahi, Photovoltaic parameter estimation using heuristic optimization, in: 2017 IEEE 4th International Conference on Knowledge-Based Engineering and Innovation (KBEI), IEEE, 2017, pp. 0792–0797.

[36] M. F. Fard, F. Elyasichamazkoti, A. F. Savadkouhi, Active distribution network optimal power flow deploying the benders decomposition method, in: 2021 IEEE Electrical Power and Energy Conference (EPEC), IEEE, 2021, pp. 378–383.

[37] A. Fguiri, C. Marvillet, M. R. Jeday, Estimation of fouling resistance in a phosphoric acid/steam heat exchanger using inverse method, Applied Thermal Engineering 192 (2021) 116935.

[38] Coal current issues & trends (2020).
URL `https://www.eia.gov/coal`

[39] Petroleum and other liquids current issues & trends (2020).
URL `https://www.eia.gov/petroleum`

[40] U.S. Energy Information Administration, U.s. utility-scale battery storage capacity continues its upward trend.
URL `https://bit.ly/2WGfzTj`

[41] U.S. Energy Information Administration, Natural gas-fired capacity continues to increase in large capacity increments (2022). doi:10.1016/j.enpol.2021.112707.

[42] U.S. Energy Information Administration, U.s. energy consumption by sector (2022).
URL `https://go.usa.gov/xndnp`

[43] U.S. Energy Information Administration, Hydropower and the environment (2021).
URL `https://go.usa.gov/xp3Ey`

[44] Y. Zheng, M. Sahraei-Ardakani, Leveraging existing water and wastewater infrastructure to develop distributed pumped storage hydropower in california, Journal of Energy Storage 34 (2021) 102204.

[45] U.S. Energy Information Administration, U.s. nuclear industry (2022).
URL `https://go.usa.gov/xpq2t`

[46] R. Murray, K. E. Holbert, Nuclear energy: an introduction to the concepts, systems, and applications of nuclear processes, Elsevier, 2014.

[47] F. I. Petrescu, A. Apicella, R. V. Petrescu, S. Kozaitis, R. Bucinell, R. Aversa, T. Abu-Lebdeh, Environmental protection through nuclear energy, American Journal of Applied Sciences 13 (9) (2016) 941–946.

[48] Power systems test case archive (2007).
URL `https://labs.ece.uw.edu/pstca/rts/pg-tcarts.htm`

[49] U.S. Environmental Protection Agency, Emissions & generation resource integrated database (egrid) (2021).
URL `https://go.usa.gov/xMEhK`

[50] Wind data and tools (2019).
URL `https://www.nrel.gov/wind/data-tools.html`

[51] Solar integration national dataset toolkit (2019).
URL `https://www.nrel.gov/grid/sind-toolkit.html`

[52] S. Dawn, P. K. Tiwari, A. K. Goswami, An approach for long term economic operations of competitive power market by optimal combined scheduling of wind turbines and facts controllers, Energy 181 (2019) 709–723.

[53] The White House, Fact sheet: President biden sets 2030 greenhouse gas pollution reduction target aimed at creating good-paying union jobs and securing u.s. leadership on clean energy technologies (2021).
URL `https://bit.ly/3iOvG8V`

[54] I. Staffell, S. Pfenninger, The increasing impact of weather on electricity supply and demand, Energy 145 (2018) 65–78.

[55] National Renewable Energy Laboratory, End-use load profiles (2022).
URL `https://go.usa.gov/xMEhS`