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# Environmental Impacts of Power Flow Control with Variable-Impedance FACTS

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# Environmental Impacts of Power Flow Control with Variable-Impedance FACTS

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***Abstract*—Growing environmental concerns as well as the decline in renewable energy project costs have led to drastic changes in the generation mix, and increasing penetration from renewable energy resources. However, the intermittency of renewable energy resources in contrast to legacy design of transmission system remains as one main obstacle against renewable energy integration. Several solutions, including energy storage, demand response and transmission system expansion have been proposed in response to this problem. Flexible ac transmission system (FACTS) devices are also shown as to offer a cost-effective solution for congestion problem in transmission system. This paper studies the environmental impacts of power flow control through FACTS devices as well as the economic benefits. Results show that implementing power flow control can effectively reduce dispatch cost and carbon emissions. However, the location of FACTS devices and renewable energy sites can critically affect carbon emission and renewable energy curtailment.**

***Index Terms*—Carbon emission, flexible ac transmission systems (FACTS), power flow control, renewable energy, solar energy, stochastic optimization, wind energy.**

## Nomenclature

**Indices**

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

**Parameters**

| | |
|---|---|
| $\nu$ | Wind speed |
| $\nu_{ci}$ | Wind turbine cut-in wind speed |
| $\nu_{co}$ | Wind turbine cut-out wind speed |
| $\nu_{rated}$ | Wind turbine rated wind speed |
| $\pi_{st}$ | Scenario 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 |
| $c^{FACTS}$ | FACTS device investment cost |
| $c_g^{nl}$ | Minimum generation cost |
| $c_g^{sd}$ | Generator shut-down cost |
| $c_g^{su}$ | Generator start-up cost |
| $c_g^{UE}$ | Energy deployment cost |
| $c_h^{FACTS}$ | hourly investment cost of FACTS |
| $c_r^{RC}$ | Renewable energy curtailment cost |
| $c_{gk}^{seg}$ | Piece-wise linear generation cost |
| $DT_g$ | Generator minimum down time |
| $G$ | Total number of generators |
| $I_O$ | PV array output current |
| $I_{SC}$ | PV array short circuit current |
| $K$ | Total number of segments in piece-wise linear cost function |
| $L$ | Total number of transmission lines |
| $P_{bt}^D$ | Real power demand at bus $b$ |
| $P_{rts}^R$ | Renewable energy generation |
| $P^S$ | Solar power generation |
| $P^W$ | Wind power generation |
| $P_g^{max}$ | Generator upper generation limit |
| $P_g^{min}$ | Generator lower generation limit |
| $P_{rated}$ | Wind turbine rated power |
| $PL^{max}$ | 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 |
| $S_{base}$ | MVA base of the system |
| $S_{FACTS}$ | FACTS device maximum compensation rating |
| $T$ | Time horizon |

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| | |
|---|---|
| $UT_g$ | Generator minimum up time |
| $V_{OC}$ | PV array open circuit voltage |

**Sets**

| | |
|---|---|
| $NG_b$ | Set of generators located at bus $b$ |
| $NL_b^+$ | Set of transmission lines flowing into bus $b$ |
| $NL_B^-$ | Set of transmission lines flowing from bus $b$ |
| $NR_b$ | Set of renewable energy resources located at bus $b$ |

**Variables**

| | |
|---|---|
| $\theta^R$ | Voltage angle on receiving bus |
| $\theta^S$ | Voltage angle on sending bus |
| $F$ | Transmission line flow direction |
| $P_{gtk}^{seg}$ | Real power generated in the $k$th 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 |

## I. Introduction

Global warming has reached alarming levels during recent decades threatening natural life on earth. Greenhouse gases (GHG) espescially carbon dioxide are known to be the main agent leading to global warming [1]. With this concern in mind, several countries have committed to decrease greenhouse generation levels by signing Paris accord [2]. Electricity Sector with 25% share of total carbon dioxide emission is one the primary areas of focus to reduce greenhouse gas generation [3]. In this respect electric utilities have started to replace their conventional fossil fuel plants with renewable energy resources such as wind and solar energy [4]. China, Brazil and the United states with installed capacity of 326 GW, 109 GW and 86 GW respectively, are the fastest growing countries in renewable energy expansion [5]. Despite all the benefits brought by renewable energy resources, they also have introduced new challenges to power grid, mainly due to the intermittent nature of these sources. Transmission system, originally designed to dispatch conventional electricity generated by fossil fuel plants cannot handle extra levels of uncertainty caused by renewable generation in the system. With increased levels of congestion balancing authorities have no choice but curtail renewable generation which, leading to significant economic loss. California Independent System Operator (CAISO) with installed renewable capacity of 7,200 MW as of 2013 and expected growth of 20,000 MW in renewable energy resources by 2020 has experienced large levels of curtailment due to congestion in transmission system. In order to decrease renewable energy curtailment, various approaches have been adopted by system operators. Transmission expansion is the most obvious solution to increase the capability of transmission system to incorporate renewable energy resources. Electric Reliability Council of Texas (ERCOT) in 2013 carried out transmission expansion leading to curtailment reduction from 17% in 2009 to 1.6% in 2013. However transmission expansion requires high investment cost, which is discouraging and furthermore the installed capacity will not be fully utilized due to the intermittency of renewable generation. Mid-continent Independent System Operator (MISO) adopted Dispatchable Intermittent Resource (DIR) protocol to address the congestion in transmission network, which reduced wind curtailment from 3.7% in 2010 to 0.8% in 2012. PJM Interconnection which experienced 3M$ lost opportunity cost as a result of renewable energy curtailment during September 2012, decided to modify its curtailment signaling process to increase the efficiency and minimize curtailment. In a similar approach CAISO changed the bidding policy to handle congestion and reduce curtailment [6].

Energy storage has been proposed as method to store renewable energy during peak renewable generation hours and shift it to lower generation hours instead of curtailing renewable generation. Various energy storage technologies including battery storage, pumped storage hydropower and compressed air storage have been introduced in literature to address the congestion problem. However, the high investment cost of energy storage is still a great drawback for this solution [7]–[9]. Demand response through exploitation of flexible loads is an alternative solution proposed in [10]. However this method is limited by availability of flexible loads.

Flexible ac transmission system (FACTS) devices have been widely studied to unlock full capabilities of transmission system [11]. FACTS devices can be used to control several parameters in transmission system including voltage phase and magnitude, shunt susceptance, and line impedance. the power flow in lines can be controlled with variable-impedance FACTS and flow can be re-routed from congested lines to less utilized lines with the main incentive of minimizing renewable energy curtailment. Variable-impedance FACTS includes several technologies including thyristor-controlled series compensators (TCSC) and Smart Wire Grid technology [12]. Variable impedance FACTS setting needs to be optimized alongside generation units commitment plan to achieve the highest capability of transmission system. [13] proposes a stochastic unit commitment model that co-optimizes FACTS impedance and thermal generation to minimize renewable energy curtailment. References [14], [15] investigate frameworks to include series FACTS devices and power flow control in electricity market as an ancillary service. The interdependence between power flow control through FACTS devices and transmission switching is explored in [16].

In many previous research, related to FACTS operation and planning, the impacts on emissions are overlooked. In systems with high share of fossil fuels such as coal and oil, minimizing cost, which is the objective of planning and operation models, does not necessarily translate to lower carbon emissions. Due to higher emission rates of cheap resources, such as coal, the power flow control will set the FACTS impedance such that these units generate more power, resulting in higher levels of carbon emissions. This paper evaluates environmental impacts of power flow control including renewable energy curtailment and carbon emission through an stochastic co-optimization model for FACTS adjustment and unit commitment. Several factors impacting the power flow control including renewable penetration level, renewable site location and conventional generation mix are studied in this paper. In order to study the power flow control, the co-optimization model is implemented on a modified version of RTS-96 system with added congestion. Results show that although implementing power flow control can effectively reduce generation cost and renewable energy curtailment, in cases that FACTS devices are installed on lines close to cheap high-emission sources, they can increase carbon emissions to reduce generation cost. The rest of this paper is organized as follows. In section II the co-optimization model for power flow control is formulated. Section III introduces the test system followed by the simulation results. Finally, section IV concludes the paper.

## II. Model Formulation

Thyristor-controlled FACTS can be effectively used to control line impedance and reduce loss in transmission network. TCSC can operate in both inductive and capacitive modes, with the inductive mode being more common. References [17], [18] have proposed linear models for FACTS devices that can be integrated into optimization model. The DC power flow model for a line is formulated as follows with $PL$ as the real power flow through the line and $B$ as the susceptance of the line changing within the desired range with FACTS installed where $\theta^S$ and $\theta^R$ indicate the sending and receiving bus voltage angles respectively.

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

However, this constraint is non-linear as $B$ is a variable that can be controlled through FACTS setting. Therefore this constraint can be rewritten by two conditional constraints as follows:

if $\theta^S - \theta^R \geq 0$:

$$B^{min}(\theta^S - \theta^R) \leq PL \leq B^{max}(\theta^S - \theta^R) \tag{2}$$

if $\theta^S - \theta^R \leq 0$:

$$B^{max}(\theta^S - \theta^R) \leq PL \leq B^{min}(\theta^S - \theta^R) \tag{3}$$

By adding a binary variable $F$ the two constraints can be written into a single constraint. The value for $F$ can be obtained from presolving the deterministic model. If the line flow is in the same direction as the imaginary flow from sending bus to the receiving bus $F$ takes the value '1'; otherwise, it will be '0'. Therefore, the power flow constraints in the lines eqipped with FACTS can be formulated as follows:

$$B^{min}F(\theta^S - \theta^R) + B^{max}(1-F)(\theta^S - \theta^R) \leq PL \tag{4}$$

$$B^{max}F(\theta^S - \theta^R) + B^{min}(1-F)(\theta^S - \theta^R) \geq PL \tag{5}$$

In order to evaluate the economic viability of FACTS devices the investment cost should be included in the model. Therefore, the thyristor-controlled FACTS investment cost is modeled and transformed to hourly figure as follows [19]:

$$c^{FACTS} = 0.0015S_{FACTS}^2 - 0.713S_{FACTS} + 153.75 \tag{6}$$

The investment cost can be converted to hourly figure using the discount rate and the lifespan of the device as follows:

$$c_h^{FACTS} = \frac{r(1+r)^n}{(1+r)^n - 1} * \frac{c^{FACTS}}{8760} \tag{7}$$

Renewable generation changes within continuous ranges which requires stochastic optimization models to include the uncertainty. Using continuous probability distribution is impractical for large-scale optimization models. Therefore, a few representative scenarios are considered for stochastic optimization. The stochastic co-optimization model with these scenarios can be formulated as follows:

$$\begin{aligned}\min \sum_{g=1}^{G}\sum_{t=1}^{T} c_g^{nl}u_{gt} + c_g^{su}v_{gt} + c_g^{sd}w_{gt} + \sum_{g=1}^{G}\sum_{t=1}^{T}\sum_{k=1}^{K} c_{gk}^{seg}P_{gtk}^{seg} \\ + \sum_{g=1}^{G}\sum_{t=1}^{T}\sum_{s=1}^{S} \pi_{st}c_g^{UE}(P_{gts}^{ru} + P_{gts}^{rd}) \\ + \sum_{r=1}^{R}\sum_{t=1}^{T}\sum_{s=1}^{S} \pi_{st}c_r^{RC}P_{rts}^{RC} + T\sum_{l=1}^{L} x_l^f c_h^{FACTS}\end{aligned} \tag{8}$$

subject to:

$$P_{gt} = \sum_{k=1}^{K} P_{gtk}^{seg} \qquad \forall g,t \tag{9}$$

$$P_{gt} + P_{gts}^{ru} - P_{gts}^{rd} \leq P_g^{max}u_{gt} \qquad \forall g,t,s \tag{10}$$

$$P_{gt} + P_{gts}^{ru} - P_{gts}^{rd} \geq P_g^{min}u_{gt} \qquad \forall g,t,s \tag{11}$$

$$v_{gt} - w_{gt} = u_{gt} - u_{gt-1} \qquad \forall g,t \tag{12}$$

$$v_{gt} + w_{gt} \leq 1 \qquad \forall g,t \tag{13}$$

$$\sum_{\tau=t-UT_g-1}^{t} v_{g\tau} \leq u_{gt} \qquad \forall g,t \tag{14}$$

$$\sum_{\tau=t-DT_g-1}^{t} w_{g\tau} \leq 1 - u_{gt} \qquad \forall g,t \tag{15}$$

$$P_{gt} - P_{gt-1} \leq 60RU_g u_{gt-1} + 10RU v_{gt} \quad \forall g, t \geq 2 \tag{16}$$

$$P_{gt-1} - P_{gt} \leq 60RD_g u_{gt} + 10RD_g w_{gt} \quad \forall g, t \geq 2 \tag{17}$$

$$0 \leq P_{gts}^{ru} \leq 10RU_g \qquad \forall g,t,s \tag{18}$$

$$0 \leq P_{gts}^{rd} \leq 10RD_g \qquad \forall g,t,s \tag{19}$$

$$-PL^{max} \leq PL_{lts} \leq PL^{max} \qquad \forall l,t,s \tag{20}$$

$$\sum_{l=1}^{L} x_l^f \leq N_{FACTS} \tag{21}$$

$$\begin{aligned} &x_l^f(F_l B_l^{min} + (1-F_l)B_l^{max})(\theta_{lts}^S - \theta_{lts}^R) \\ &\quad +((1-x_l^f)B_l(\theta_{lts}^S - \theta_{lts}^R) \leq PL_{lts} \quad \forall l,t,s \end{aligned} \tag{22}$$

$$\begin{aligned} &x_l^f(F_l B_l^{max} + (1-F_l)B_l^{min})(\theta_{lts}^S - \theta_{lts}^R) \\ &\quad +((1-x_l^f)B_l(\theta_{lts}^S - \theta_{lts}^R) \geq PL_{lts} \quad \forall l,t,s \end{aligned} \tag{23}$$

$$\begin{aligned} &\sum_{g \in NG_b} (P_{gt} + P_{gts}^{ru} - P_{gts}^{rd}) + \sum_{r \in NR_b} (P_{rts}^R - P_{rts}^{RC}) \\ &+ \sum_{l \in NL_b^+} PL_{lts} - \sum_{l \in NL_b^-} PL_{lts} = P_{bt}^D \qquad \forall b,t,s \end{aligned} \tag{24}$$

The model above seeks to minimize dispatchable generation cost and renewable curtailment opportunity cost (8) with respect to generator constraints including minimum and maximum generation (10)-(11), generator minimimum up and down time (14)-(15) and ramping constraints (16)-(19) as well as line dc power flow and maximum capacity constrains (20)-(23). In this model, if $x_l^f$ is introduced as a variable for optimal FACTS allocation the problem would be a mixed-integer nonlinear programming (MINLP), which needs to be linearized for large-scale networks. In this study since FACTS are already installed in one of candidate line for evaluation, $x_l^f$ is simply treated as a parameter and the model is mixed-integer linear programming.

## III. Simulation Studies

The simulations are carried out on modified single-area RTS-96 with 24 buses [20]. In order to create congestion in transmission system, capacity of lines A21-1 and A25-2 is reduced to 175 MW and ratings of A21 and A22 reduced to 220 MW. Furthermore, 480 MW of load is shifted from buses 14, 15, 19 and 20 to bus 13; then, load on each bus is increased by 5%. Three pairs of candidate buses are considered as prospective sites for renewable energy resources. Buses 4,5 represent renewable sites close to demand, buses 17,18 indicate sites close to low-cost generation units and finally buses 3,24 are typical buses in transmission system. Three candidate lines are considered for FACTS installation. Lines A21 and A25-1 are taken as highly utilized lines and A26 as large capacity line that can be used as an alternate route for power flow. For renewable energy integration, two 400 MW wind units and two 175 MW solar units are considered with scenarios based on historical data from National Renewable Energy Laboratory (NREL) [21] [22]. The maximum adjustment range of -80% to 40% is considered for thyristor-controlled FACTS in this study. RTS-96 generation mix is shown in figure 1. Coal-fueled units comprise the largest share of generation mix for RTS-96. Coal can be in several forms with different carbon emission level and energy density. lignite is the most abundant form of coal with lowest level of stored energy. Subbituminous and bituminous also known as soft coal have higher stored energy compared to lignite. Finally anthracite, the most infrequent type of coal has highest level of stored energy. Heavy oil is the second type of energy source in RTS-96 generation mix and has similar levels of greenhouse gas emission to coal-fired generators [23]. Nuclear energy resources do not produce any carbon emission; however, the nuclear waste produced by these generation units is may be an environmental concern too. Finally, hydropower units can be regarded as dispatchable renewable units with zero carbon emission and generation cost. The emission rate and generation cost for each plant type is shown in Table I.

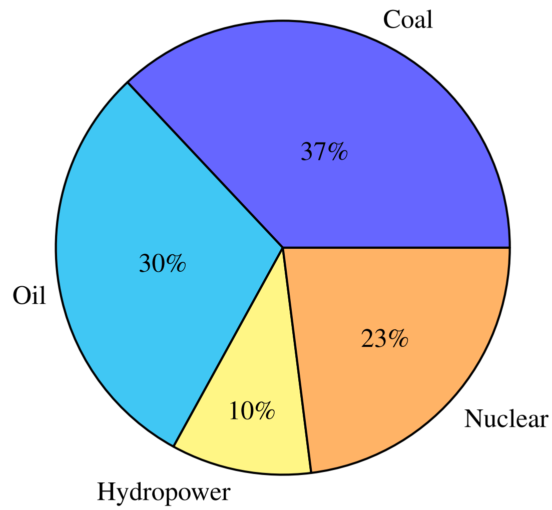


Fig. 1. RTS-96 Generation Mix

TABLE I
AVERAGE CARBON EMISSION AND GENERATION COST FOR PLANT TYPES

| | Emission Rate (lb/MWh) | Generation Cost ($/MWh) |
|---|---|---|
| Coal-fired | 2027.09 | 21.52 |
| Oil-fired | 1670.99 | 120.86 |
| Gas-fired | 1168.86 | 14.45 |
| Nuclear | 0 | 2.27 |
| Hydropower | 0 | 0 |

In the first section of simulation studies the impact of power flow control implementation on total dispatch cost and carbon emissions is studied. In this respect, different number of lines in modified RTS-96 system are equipped with FACTS devices in each simulation and the results are indicated in table II. As the results show, installing FACTS devices would reduce generation cost by providing the flexibility in

TABLE II
SIMULATION RESULTS FOR RTS-96 WITHOUT RENEWABLE ENERGY RESOURCES

| Number of FACTS | FACTS Location (Line) | Total Generation Cost(M$) | Carbon Emission (Mlb) |
|---|---|---|---|
| 0 | N/A | 1.981 | 66.291 |
| 1 | 21 | 1.712 | 67.221 |
| 2 | 25,26 | 1.885 | 63.643 |
| 3 | 21,25,26 | 1.645 | 64.420 |

transmission system to use the capacity of cheaper energy resources. However, installing FACTS on line 21 increases the carbon emission although it improves dispatch cost. This is mainly due to the fact that line 21 is in the proximity of coal-fired units which are characterized by higher emission rates and lower generation cost. Therefore, the optimization model increases the coal units generation which consequently results in higher emission.

In the next section of studies, the impact of power flow control on renewable energy resources is studied. 24 simulations are carried out, placing solar and wind units on different candidate buses and FACTS devices on candidate lines and the results include generation cost, renewable energy curtailment and carbon emissions are indicated in Tables III,IV. Results show that installing renewable energy resources can effectively reduce generation cost and carbon emission by replacing costly and polluting fossil-fueled units. Cost savings and emission reductions are more significant for wind integration case, since wind is less intermittent compared to solar energy, which is unavailable for almost half of the day. Installing FACTS would decrease generation cost and emission except for the case that FACTS are installed close to cheap high emission units. Renewable energy curtailment is increased in some cases, mainly because configuring the transmission system to use other low-cost energy sources would bring more cost saving. The location of renewable energy resources is a determining factor in this regard. Renewable energy curtailment is highest when renewable energy sites are located at buses 17 and 18 mainly due the fact that these buses are close to other low-cost units which bring higher levels of congestion in the neighboring area and results in more renewable energy curtailment. Note that we do not include the investment cost for renewable generation in our analysis. We assume that renewable plants are already planned for compare the operation cost only. The FACTS investment cost is converted to an hourly figure and included in the analysis to reveal the benefits of installing FACTS, if any.

Finally, the impact of variable-impedance FACTS is evaluated for different levels of renewable energy resources. 24 simulations are carried out for penetration levels from 0% to 65% and the cost savings, emission reduction and renewable energy curtailment for each case is indicated in Figs. 2, 3 and 4 respectively. Renewable energy integration can bring about cost saving up to 34%, which can be further increased to 46% by implementing power flow control. It should be noticed that installing FACTS on line 21 saves more cost although it increases emission due to proximity to cheap coal-fired units. Emission is reduced up to 32% at the highest renewable penetration level with FACTS devices providing extra flexibility in transmission system. However, FACTS devices do not necessarily reduce renewable energy curtailment owing to the fact that spillage is highly affected by renewable site location.

TABLE III
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 | 1.604 | 54.831 | 1458.83 |
| | 1 | 21 | 1.388 | 55.822 | 1559.59 |
| | 2 | 25,26 | 1.526 | 52.213 | 1515.28 |
| | 3 | 21,25,26 | 1.332 | 53.180 | 1664.19 |
| 4,5 | 0 | N/A | 1.522 | 54.448 | 454.63 |
| | 1 | 21 | 1.318 | 55.038 | 363.65 |
| | 2 | 25,26 | 1.440 | 51.649 | 452.53 |
| | 3 | 21,25,26 | 1.255 | 52.382 | 399.89 |
| 17,18 | 0 | N/A | 1.879 | 63.263 | 600.49 |
| | 1 | 21 | 1.629 | 64.248 | 619.67 |
| | 2 | 25,26 | 1.791 | 60.505 | 452.96 |
| | 3 | 21,25,26 | 1.556 | 61.193 | 452.96 |

TABLE IV
SIMULATION RESULTS FOR RTS-96 WITH SOLAR 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 | 1.783 | 62.307 | 0 |
| | 1 | 21 | 1.534 | 63.075 | 35.62 |
| | 2 | 25,26 | 1.695 | 59.438 | 0.85 |
| | 3 | 21,25,26 | 1.471 | 60.346 | 62.23 |
| 4,5 | 0 | N/A | 1.744 | 63.214 | 0 |
| | 1 | 21 | 1.502 | 63.702 | 0 |
| | 2 | 25,26 | 1.653 | 60.322 | 0 |
| | 3 | 21,25,26 | 1.431 | 61.162 | 0 |
| 17,18 | 0 | N/A | 1.933 | 65.245 | 0 |
| | 1 | 21 | 1.675 | 66.044 | 0 |
| | 2 | 25,26 | 1.840 | 62.303 | 0 |
| | 3 | 21,25,26 | 1.600 | 63.165 | 0 |

## IV. CONCLUSIONS

This paper investigated the environmental impacts of power flow control as well as economic benefits of flexibility in transmission system through implementing FACTS co-optimization model on RTS-96 system. FACTS devices can effectively reduce generation cost by unlocking transmission system capability to utilize low-cost generating units. However carbon emissions increase when FACTS devices are installed close to high-emission generation such as coal-fired units. Renewable

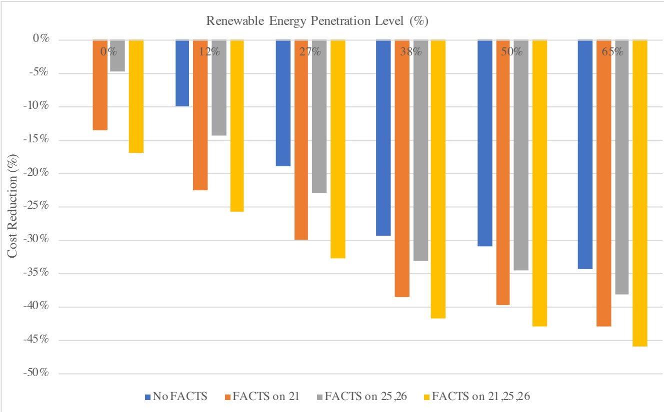


Fig. 2. Cost Saving for Renewable Energy Penetration Levels

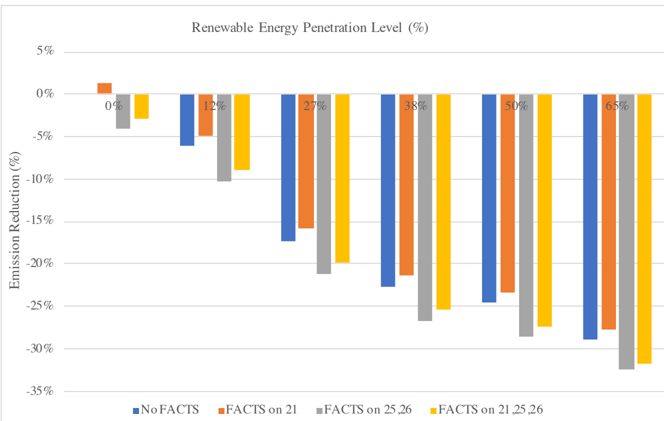


Fig. 3. Emission Reduction for Renewable Energy Penetration Levels

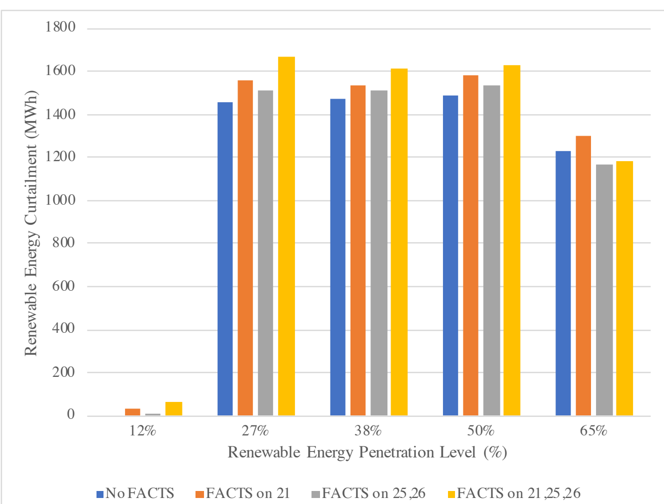


Fig. 4. Renewable Energy Curtailment for Renewable Energy Penetration Levels

energy integration is facilitated by implementing power flow control. However, the renewable energy spillage is highly dependent upon renewable site location and proximity of FACTS. The generation mix and other types of fossil fuel share in real-life cases is another significant factor in FACTS effectiveness in carbon emission reduction, which will be addressed in our future work.

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