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# ENHANCING NETWORK UTILISATION IN WIND-RICH REGIONS USING COORDINATED DYNAMIC LINE RATING, ENERGY STORAGE AND POWER FLOW CONTROL SCHEMES

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**Keywords:** Dynamic line rating, energy storage systems, static series compensation, congestion management

## Abstract

Increasing wind energy utilisation, along with demand growth, are impacting on transmission system regional loading. Traditionally, uprating of existing lines and construction of new lines would have been common approaches to increase network capacity and reduce congestion. However, environmental, social, and technical challenges are encouraging network operators to apply measures which improve utilisation of the existing network, as part of future planning. Here, a mixed integer linear programming model is developed to integrate various alternative options, including dynamic line rating, energy storage systems and distributed static series compensation, into the network planning process. Using a multi-stage approach, co-optimised planning of these assets is studied and compared against a conventional reconductoring approach. The benefits of co-optimisation are shown for the IEEE RTS 24 bus system, with high wind contributions in selected regions.

## 1. Introduction

With increasing installations of wind farms, and a growth in electrical demand, the subsequent desire to expand the transmission and distribution systems can become ever more challenging from technical, environmental, and social viewpoints, and obtaining rights of way (RoW) for new lines can become increasingly difficult. There is an increasing need, therefore, to utilise existing RoWs to manage network congestion, as much as possible, in order to facilitate further renewables and load growth. Increasing transmission system capacity has traditionally been based on reinforcing the system through reconductoring, voltage upgrades of existing lines, or construction of new lines. The lead time for such expansion projects has typically been long, comparable to the timescales associated with constructing a conventional power plant, i.e.  $\approx 8$ -10 years. However, in more recent times, the lead times for solar plants and wind farms, often located in remote locations, has been much shorter. In order to more quickly adapt network expansion plans, network congestion can be managed using more active, and shorter lead time, corrective solutions, e.g. dynamic line rating (DLR), power flow controllers (PFC) and energy storage systems (ESS).

Traditional engineering practice for transmission line design considers worst-case scenarios for (seasonal) static ratings. However, local weather conditions may enable individual lines to provide additional capacity at certain times, which can potentially be utilised using DLR schemes. The available headroom can be determined based on measurement of local weather conditions or conductor tension [1]. DLR can be most applicable when transferring power from wind farm clusters, due to the likely strong correlation between wind farm outputs and line cooling effects. However, longer-term load growth may challenge DLR schemes, since it may not always be windy during peak load periods. DLR is often seen as an attractive option for expansion planning studies, being

comparatively low cost with relatively short installation times [2]. As part of power flow analysis, or optimal power flow, two distinct modelling approaches are typically adopted. Firstly, the temperature gradient is included in the heat balance equation, whereby, dynamics lasting less than one hour are considered [3]. Alternatively, thermal dynamics are ignored, and line thermal capacities are determined based upon "steady-state" weather conditions [1][4]. The former approach is more suited for operational applications, while the latter is more efficient for planning studies.

Utilisation of energy storage systems (ESS) in power grids can potentially resolve reliability, security, and stability problems. In addition, they can promote energy balancing, and provide a convenient offline source of contingency and operating reserve. Alleviating transmission challenges can also be valuable by means of deferring upgrades or reducing system expansion costs [5]. As a specific case, temporary congestion, e.g. overloads arising from contingencies, can be handled using such measures [6]. ESS placement has been implemented within optimisation models, which minimise operational cost, as well as fulfilling transmission constraints, which assist with congestion management. In order to maintain problem tractability, representative days across a year are usually assumed. In addition, a DC-OPF model can be applied, such as in [7], where a multi-stage approach is developed for placement of battery energy storage systems, involving both locational and installation time aspects.

Alternatively, power flow controllers, deployed in series with the network, can control the flow along individual branches. Series flexible ac transmission systems (FACTS) provide significant capability to manage network congestion, but this comes with cost and technical challenges[8]. In contrast, distributed-FACTS (D-FACTS) are a newer option, offering reduced cost and easier deployment. One example here is the

distributed static series compensator (DSSC), which modifies line impedance to "push" or "pull" current into a transmission line, by generating a voltage in quadrature to the line current. These low power (up to 20 kVAr) modules can typically be clamped to an overhead line [9], providing a cost-effective solution to increase transfer capacity. Placement of DSSC devices can aim to increase line loadability [12], while satisfying a predefined reliability index, and utilising a linear optimisation formulation, e.g. DC-OPF, for planning [11].

Given the availability of the above technologies, it follows that future network planning should consider strategies which can reduce or delay network investment. However, while studies have considered individual technologies [1][7][10], they have not generally been investigated collectively. Here, the objective is to develop a methodology which identifies lines which could benefit from installing DLR, and/or DSSC, and, identify those locations best suited for ESS installation, in order to minimise capital investment, while improving network utilisation and minimising the total system cost. A medium-term planning horizon is assumed (< 10 years), such that the focus is placed on using existing RoWs, and not constructing new lines, which may take longer to achieve.

The main paper contributions are threefold: development of a MILP multi-asset model for multi-stage transmission planning, utilising DLR, DSSC, ESS, and reconductoring, to minimise network congestion; introducing a formulation which enables concurrent investment actions for individual lines e.g. DSSC placement on lines which are already seen as candidates for DLR or reconductoring; and, then later co-optimisation of co-ordinated schemes to manage congestion. The paper is organised as follows: Section 2 presents the methodology and preparation of model inputs, leading to the optimisation model in Section 3. The test network is introduced in Section 4 and finally, results and conclusions are presented in Sections 5 and 6.

## 2. Methodology

Congestion management is studied using the methodology shown in Fig. 1. For this study, the optimisation model requires a range of scenarios, prepared based on likely weather and system load forecasts for the planning horizon. Lacking such information, historical data can be utilised, with different scenarios generated using probability distribution functions. Solar irradiation, ambient temperature, wind speed, and load profile time series are required as part of scenario generation, which is performed here using a fast forward selection algorithm [15], leading to the selection of a limited number of representative days for each planning year. For each day, the DLR potential for individual lines and the maximum wind power potential is calculated, as part of model initialisation. The optimisation process then manages congestion through identifying those lines which would benefit from DLR, DSSC placement and/or reconductoring, as well as buses requiring ESS installation. The overlapping sets of identified lines in Fig. 1 acknowledges the possibility of concurrent investments.

DLR calculations are based on steady-state heat balancing, whereby the resistive and solar heat gains balance the convective cooling and radiated heat loss:

$$R_{T_C} I^2 + q_s = q_c + q_r \quad (1)$$

where  $I$  is the electrical current,  $T_C$  the maximum conductor temperature,  $R_{T_C}$  the electrical resistance at temperature  $T_C$ , with  $q_s$  solar heating,  $q_c$  convective cooling and  $q_r$  radiated heat loss. Details of  $q_c$ ,  $q_r$  and  $q_s$  dependencies on weather conditions, such as wind speed, solar irradiation and ambient temperature are found in [12]. The DLR time series are calculated for each representative day and conductor type using (1), and then fed to the optimisation model. The wind incidence angle is assumed to be zero, to adapt DLR for all line directions, while the impact of DLR-induced voltage drops (since only DC load flow is applied here) is considered by setting line length limits, i.e. only short lines considered here (< 80 km [1]). Typically, voltage support is investigated in subsequent planning stages.

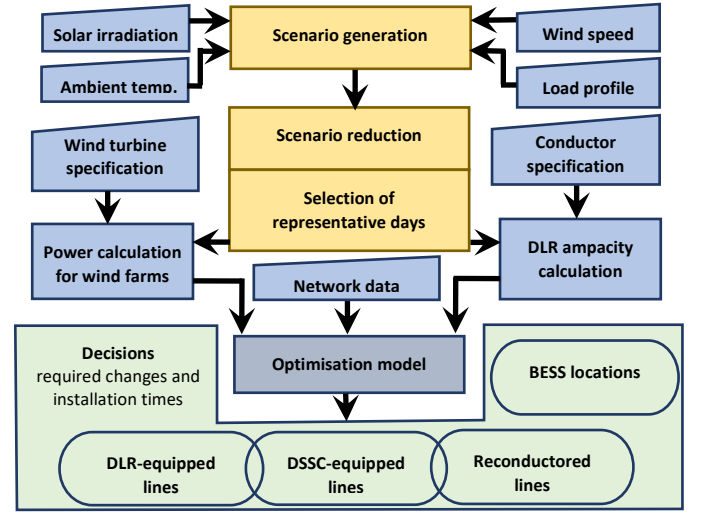


Fig. 1 Methodology flowchart

## 3. Optimisation model

In order to identify the preferred planning option, based on the least cost sum of operational and capital costs, an optimisation model has been developed here. The model is formulated based on a weighting parameter,  $w_{sc,y}$ , obtained from scenario reduction, representing the weight of a relevant representative day (scenario  $sc$ ) in year  $y$  [15]. In addition, a multi-stage representation is used, which captures the year when new assets are expected to be installed. The objective function is formulated to minimise fuel cost, and potential load shedding, as well as the capital cost of the new assets:

$$\text{Minimise: } C_{total} = C_{operational} + C_{load-shed} + C_{ess} + C_{dssc} + C_{line\ modification} \quad (2)$$

The operational cost for generation (fuel), and, the load shedding cost, are formulated separately as follows:

$$C_{operational} = \sum_{y(t)} \left( \frac{1}{1+dr} \right)^{t-1} \sum_{sc} w_{sc,y} \sum_h \sum_g C_g P_{g,y,sc,h} \quad (3)$$

$$C_{load-shed} = \sum_{y(t)} \left( \frac{1}{1+dr} \right)^{t-1} \sum_{sc} w_{sc,y} \sum_h \sum_t C_{sh} L S_{i,y,sc,h} \quad (4)$$

where,  $dr$  represents the discount rate,  $t$ , the year index,  $C_{sh}$ , per unit load curtailment cost,  $C_g$ , unit  $g$  generator cost,  $P_{g,y,sc,h}$ , active power of unit  $g$ , and  $LS_{i,y,sc,h}$ , load shedding at bus  $i$ , in year  $y$ , scenario  $sc$ , hour  $h$ . In addition, the capital costs for assets under study are determined as follows:

$$C_{line\ mod.} = \sum_{y(t)} \left( \frac{1}{1+dr} \right)^{t-1} \sum_l \sum_{lop} C_{l,lop} (b_{l,lop,y(t)} - b_{l,lop,y(t-1)}) \quad (5)$$

$$C_{ess} = \sum_{y(t)} \left( \frac{1}{1+dr} \right)^{t-1} \sum_e C_{ess,e} (op_{e,y(t)} - op_{e,y(t-1)}) \quad (6)$$

$$C_{dssc} = \sum_{y(t)} \left( \frac{1}{1+dr} \right)^{t-1} \left( \sum_d C_{dssc,d} (op_{d,y(t)} - op_{d,y(t-1)}) + \sum_d \sum_{lop} C_{dssc,d,lop} (op_{d,lop,y(t)} - op_{d,lop,y(t-1)}) \right) \quad (7)$$

In (5),  $b_{l,lop,y}$  represents a binary decision variable for implementing option  $lop$  for line  $l$  in year  $y$  (e.g. DLR or reconductoring), while  $C_{l,lop}$  represents the associated capital cost. In (6),  $op_{e,y}$  is the decision variable for ESS capacity,  $e$ , installed in year  $y$ , with, similarly,  $C_{ess,e}$  being the associated capital installation cost. In (7),  $op_{d,y}$  and  $op_{d,lop,y}$  represent decision variables for the total DSSC capacity  $d$  installed in year  $y$ , on the unmodified relevant line, and on the relevant line modified by option  $lop$ , respectively, and, again,  $C_{dssc,d}$  and  $C_{dssc,d,lop}$  are the associated capital costs. For the above investment decisions,  $b_{l,lop,y}$  is the only binary decision variable, with the other decision variables assumed continuous within a 0-1 range, to represent a progressive installation approach for relevant assets.

For network analysis, DC power flow is utilised. A detailed representation of individual line constraints is now presented, but it is recognised that some expressions could be simplified where unneeded (investment related) variables don't apply. For example, the flow constraint is formulated to include a phase angle shift for lines which are candidates for DSSC installation:

$$f_{l(i,j),y,sc,h} = (\theta_{i,y,sc,h} - \theta_{j,y,sc,h} + \theta_{d,y,sc,h}) B_l \quad (8)$$

where  $f_{l(i,j),y,sc,h}$  represents power flow on line  $l$ , connected between buses  $i$  and  $j$ ,  $\theta_{i,y,sc,h}$ , the phase angle at bus  $i$ , and  $\theta_{d,y,sc,h}$ , the DSSC,  $d$ , induced phase shift [11]. All variables apply for year  $y$ , scenario  $sc$ , and, hour  $h$ , and  $B_l$  represents the susceptance of line  $l$ . Thermal line constraints, generation operating ranges, renewable energy curtailment, and load shedding (if required) are implemented using standard inequalities. However, for candidate lines for modification (e.g. DLR or reconductoring), further constraints are added:

$$|f_{l,y,sc,h}| \leq \sum_{lop} (f_{max_{l,lop}} - f_{max_l}) b_{l,lop,y} + f_{max_l} \quad (9)$$

$$\sum_{lop} b_{l,lop,y} \leq 1 \quad (10)$$

$$b_{l,lop,y(t)} \geq b_{l,lop,y(t-1)} \quad (11)$$

In (9),  $f_{max_l}$  and  $f_{max_{l,lop}}$  represent the transfer (MW) limit of line  $l$ , pre- and post-implementation of option  $lop$ . Where DLR is considered, a pre-calculated time series provides  $f_{max_{l,lop}}$  values for each hour (Section 2). In addition, (10) enforces, at most, one modification for each line  $l$  in the relevant set, while (11) ensures that  $b_{l,lop,y}$  remains high in subsequent years after first activation.

Battery ESS systems are modelled based upon a pre-defined discharge time, and include essential variables, i.e. state of charge (SOC), charge / discharge power, as bound by the decision variable  $op_{e,y}$  [7]. A power balancing constraint is formulated based on thermal generation, renewables or ESS at individual buses. Moreover, load shedding and renewable energy curtailment are included. Finally, DSSC constraints for candidate lines to be modified are formed as follows:

$$op_{d,y(t)} \geq op_{d,y(t-1)} \quad (12)$$

$$op_{d,lop,y} \leq b_{l,lop,y} \quad (13)$$

$$b_{d,y} \times \theta_{min} \leq op_{d,y} \quad (14)$$

$$op_{d,y} \leq b_{d,y} \quad (15)$$

$$|\theta_{d,y,sc,h}| \leq \sum_{lop} op_{d,lop,y} \times \theta_{max_{d,lop}} + op_{d,y} \times \theta_{max_d} \quad (16)$$

$\theta_{max_d}$  represents maximum permitted DSSC compensation for a line [11], with  $\theta_{min}$  being the minimum (non-zero) level of compensation [10], and,  $b_{d,y}$ , an auxiliary binary variable enforcing a minimum compensation level. The  $lop$  subscript acknowledges the installation of DSSCs on lines which are already candidates to be modified (e.g. DLR installation or reconductoring). Eqn. (12) ensures a continuous progressive installation approach, while (13) forces  $op_{d,lop,y}$  to be active only when  $lop$  applies to line  $l$ . (14) and (15) satisfy minimum compensation levels (similar inequalities also apply to  $op_{d,lop,y}$ ), and (16) limits  $\theta_{d,y,sc,h}$  to permissible compensation levels.

If a line is modified by option  $lop$ , and, in addition, also selected for DSSC installation, higher current levels through the DSSC will result, due to an increase in line capacity, compared to the unmodified case. Hence, for the same level of reactive compensation, DSSCs should collectively induce a higher voltage, such that  $\theta_{max_d}$  should be increased to  $\theta_{max_{d,lop}}$ , with the DSSC nominal current selected according to that of the modified line. Finally, the total number of DSSC devices installed on each line is found as the integer solution of multiplying the relevant decision variable and the maximum compensation level over the unit nominal voltage.

#### 4. Case study

A planning horizon of 10 years is chosen, based upon 20 representative days for each year. Ideally, individual, but correlated, wind speed time series would be used for different locations, to represent wind farm generation and line cooling effects. However, for a planning phase, a single wind speed profile has been employed, extrapolated for typical wind turbine hub heights and line conductor heights [14]. Wind speed and ambient temperature data were obtained from [13] for Shannon airport weather station, Ireland, with maximum

solar irradiation for each hour calculated based on Ireland's latitude [12]. Consequently, DLR impacts can be expected to be slightly conservative. Weibull and normal distributions are applied in scenario generation for ambient temperature, wind speed and solar irradiation, based upon assumed mean values obtained from weather data. Calculated dynamic line rating values are scaled here by a factor of 0.9, as a prudent measure [1].

The IEEE RTS 24 bus system is selected as the test system [15], essentially consisting of two sub-systems, as seen in Fig. 2. In order to adapt the network for study, Dove and Curlew conductors are assumed for the 138 kV and 230 kV lines. The peak load is initially assumed as 2,250 MW, with an annual growth rate of 3% per annum, resulting in a peak of 2,900 MW at the end of the study horizon. Annual historical load profiles from 2015 for the Irish grid have been utilised, scaled to match the defined load peak, and considered as part of scenario generation using a normal distribution.

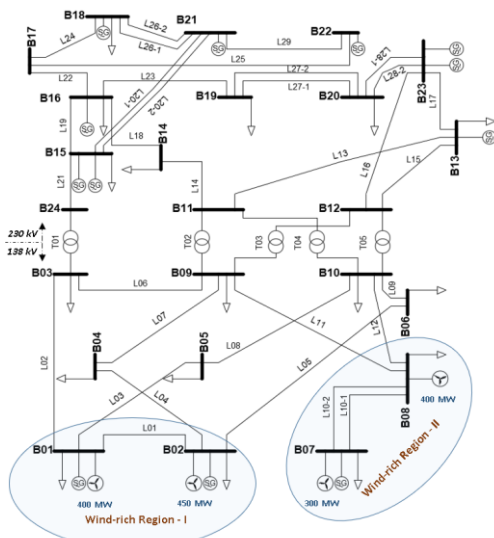


Fig. 2 Modified IEEE RTS 24 bus network

As transformer upgrades are not the focus here, it is assumed that the 230/138 kV transformers are rated at 500 MVA, to account for expected load growth. Moreover, an additional line is considered between Buses 07 and 08, to facilitate wind energy transfer. In addition, four wind farms are placed at selected buses, to effectively create "wind rich" regions, with capacities chosen such that network capacity is sufficient, with a margin, to meet local peak demand under local supply conditions in year 1. Annual wind power capacity growth is set at twice the demand growth rate, emphasising the impact of faster renewables capacity growth in many systems. However, unit commitment procedures are not implemented here, such that existing thermal units are not de-committed during high wind periods, although generator minimum outputs are reduced from the original data. The model was developed and formulated using Python 3.7 as the programming environment, with the Gurobi 9.0.1 solver.

## 5. Results

Using the modified IEEE RTS system, congestion relief is now studied using eligible assets, including DLR, DSSC, ESS and

ACSR reconductoring. Initially, congestion is investigated across the 10 year test period without network modifications, in Section 5.1, before subsequently enabling network modifications, but restricting asset deployment to one device per line, and then finally permitting multiple assets to be deployed per line, e.g. DLR employment in conjunction with DSSC devices.

A pre-selection process is employed to select potential candidate lines for study, based on the weighted locational marginal price (LMP) for the entire planning horizon at individual buses, normalised by the modification cost [12]. For DSSCs, the candidate line set also includes neighbouring lines to those selected by the LMP criterion, as their line flows will be indirectly affected. DSSC units with a 20 kVAr rating, and the same current rating as the associated line are assumed, with a 20% upper limit on reactive compensation. Suitable buses for ESS placement are typically found at the ends of congested lines [6], and it is assumed that each substation can host batteries with specifications of  $SOC_{max} = 100$  MWh,  $P_{charge} = P_{discharge} = 25$  MW and  $\eta_{round-trip} = 85\%$ . ACSR reconductoring is based upon assuming twin conductors with an ampacity increase twice that of an unmodified line. Finally, in order to avoid problem infeasibility for the default and single-asset solution cases, load shedding, but with a penalty cost of 10,000 €/MWh, is assumed. Wind curtailment is possible without any direct penalty. A capital investment discount rate of 5% is also considered.

### 5.1. Base case

In the base case, optimal power flow is performed for the 10 year study horizon, assuming load and renewable generation growth (summarised in Section 4), but without any network modifications. A sharp increase in the load shedding volume occurs from year 7 onwards, notably at bus-05 and bus-06 with a volume of 2.0 GWh (0.014% of total annual demand) for the final year, as the available capacity of lines L08 and L09 is insufficient to supply the demand, particularly during peak demand periods.

### 5.2. Single-asset deployment for congestion relief

If it is now assumed that, at most, a single "action" can be performed, e.g. DSSC installation, Fig. 3 presents the costs obtained, including capital cost, operational (generation) cost, and total cost across the 10 year period, which also includes the likely load curtailment cost (Eqn. 2).

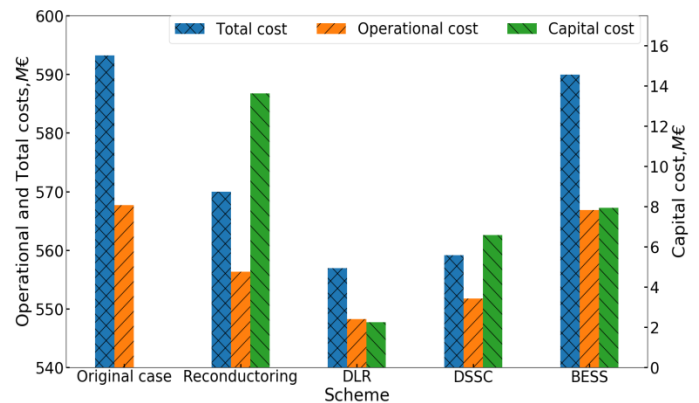


Fig. 3 Cost comparison for single-asset treatment

Using DLR-only and DSSC-only schemes, the total cost reduces by 6.1% and 5.7%, respectively compared to the base case, while reconductoring reduces the cost by 3.9%. The DLR and DSSC options tend to be much cheaper ( $\approx 17\%$  and  $48\%$  of reconductoring capital cost). This result is certainly not unexpected, as the performance of DLR and DSSC schemes is significantly higher for a grid with a large share of wind energy, as is the case for the system under study. In the scenario generation and reduction stages, a common seed wind speed is assumed, which is scaled for DLR and wind power calculations, which results in optimistic correlations and favourable DLR performance. However, the DLR and DSSC schemes do result in some load shedding of  $\approx 0.006\%$  and  $0.001\%$  of total annual demand for the final planning year, and although this does improve upon the base case, reconductoring avoids load shedding. Here, reconductoring involves uprating line L03 in year 4 (to facilitate wind energy transmission), and lines L08 and L09 in years 7 and 9 (to avoid load shedding at bus-05 and bus-06).

BESS utilisation is not highly favoured, with load shedding deployed as a more cost-effective option. A BESS capacity of  $\approx 50$  MWh is determined to be installed at bus-05 in year 7, leading to a load curtailment of  $0.01\%$  of total annual demand in the final year, and a  $0.5\%$  cost saving against the base case. It follows from the above that co-planning of different assets can impact load shedding while reducing the total cost, which is the subject of the next analysis.

### 5.3. Multiple-asset deployment for congestion relief

Instead of being restricted to implementing a single solution option, the optimisation model is now given the freedom to implement multiple options for a given set of candidate lines, potentially at different times in the planning horizon. All congestion relieving assets studied here are made available for the optimisation model to select, including DLR, DSSC, BESS and reconductoring. From the model formulation, candidate lines can benefit from a single modification (DLR or reconductoring), and/or concurrently, DSSC placement, while candidate buses for BESS placement can host storage units independently. The least cost plan is achieved involving DLR and DSSC installation, as depicted in Fig. 4.

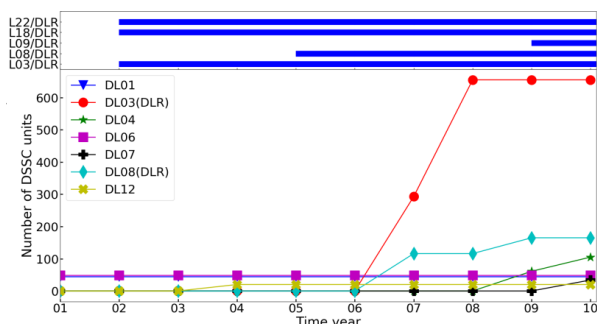


Fig. 4 Least cost scheme – DLR installation (top) and total number of DSSC units (lower) across planning horizon.

BESS and reconductoring options are not preferred by the model, as more efficient and cheaper options, i.e. DLR and DSSC assets, are now available and provide a reasonable solution without needing to load shed. In this plan, lines L03 and L08 are selected for both DLR and DSSC installation. It

should be noted that since DSSCs are installed on both lines they must be able to support the higher current associated with the DLR scheme, previously chosen for these lines, as explained in Section 2. In this study, the maximum DLR value was calculated as twice the SLR, although, depending on capacity limits of substation equipment, identification of DLR critical spans, etc, practical rating improvements may be somewhat lower, and require detailed study for specific cases. Therefore, the current rating for these DSSCs should be doubled, with the same power rating. Cost figures relevant to the least cost scheme are compared with other co-planning schemes in Section 5.4.

### 5.4. Bi-asset deployment for congestion relief

Finally, combinations of two options are now enabled for the model to select from. These co-planning schemes can provide feasible solutions without load curtailment, so in order to compare combinations equitably, the ability to load shed is now disabled. The cost results are presented in Fig. 5 and compared against reconductoring costs. The capital cost for the DLR+DSSC scheme (Section 5.3) is  $82\%$  lower than the reconductoring option, and proves to be the most economic congestion relief plan here with a total cost  $3.3\%$  less than reconductoring. Meanwhile, the BESS+DLR scheme presents the lowest operational cost, but the capital costs are relatively high ( $13\%$  higher than reconductoring). Both BESS-based schemes achieve a total cost  $\approx 1.5\%$  less than reconductoring, on average. However, reconductoring together with DSSC or DLR reduces the capital cost by  $17\%$  and  $51\%$ , and the same trend can be observed for the total (operational) cost, which reduces by  $1.7\%$  and  $2.6\%$ .

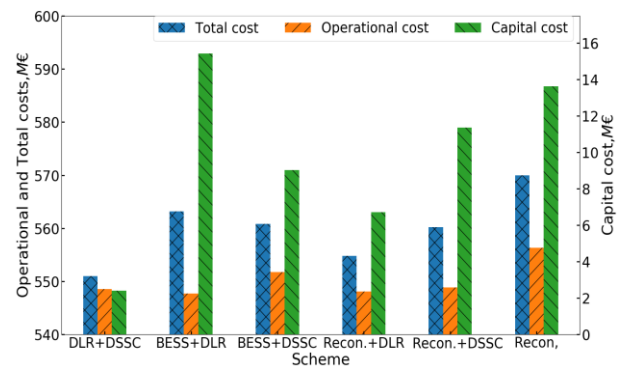


Fig. 5 Cost comparison for dual-asset treatment

Combining the reconductoring and DSSC options results in reconductoring for line L03 and DSSC installations on several lines, including line L03 which is connected to bus-05 (one of the sources of congestion), and, line L08, the neighbouring line, at the maximum permissible compensation level. These actions, together with the DLR+DSSC results obtained in Section 5.3, suggest that placing DSSCs on lines previously selected for other modifications can be beneficial for enhanced network utilisation. It should be noted that generally such deployment is costly, as DSSCs must be selected with higher ampacity rating for modified lines, and instead, it can be more cost-effective to place them on unmodified neighbouring lines. However, it remains a viable solution if installation of DSSC on neighbouring lines is not practical, such as when the maximum compensation level is reached (adjacent to major

congestion points, e.g. bus-05). Hence, concurrent investment has limited application, but can be considered for lines connecting to congestion sources, which, in turn, greatly reduces the calculation burden.

## 6. Conclusions

A MILP model for multi-asset congestion management has been formulated, which incorporates a range of investment options, including reconductoring, DLR for individual lines, and placement of DSSC and BESS units. Specifically, a formulation is presented to study DSSC placement on lines previously selected for modification.

Although single-option planning has been investigated for individual lines, co-optimisation of different solution options was seen as essential, with a progression of options being appropriate on a multi-year timescale. Dynamic line rating, in conjunction with the installation of distributed static series compensation, can often be more economic, and selectively address congestion over more costly reconductoring options. It can also form an important contribution to multi-year least cost solutions through comparatively fast installation, before reconductoring at a future point. BESS placement was seen as a comparatively expensive option, as part of a network congestion focussed approach, although the ability of storage to achieve multiple revenue streams, for example, energy arbitrage and reserve provision, could significantly improve the economic viability of such an approach.

The proposed approach increases model complexity, and, for a realistic system study, a decomposed structure is likely to be required. In order to fully capture future uncertainties and generate appropriate scenarios, more detailed approaches may also need to be implemented. It is also noted that optimisation decisions can be subject to assumptions around costs, demand and RES generation growth, etc., such that sensitivity analysis will be studied to improve the robustness of decisions made. Network voltage profiles and reactive power requirements require analysis in the context of the new active network devices. In future work, unit commitment scheduling, operational reserves, and security constraints will be studied within a decomposed co-optimisation structure. Moreover, DLR performance will be examined with more realistic regional input data, an AC power flow model and a test system utilising PV power plants.

## Appendix-I

Table 1 Cost data

Asset	Cost <sup>1</sup>	Project Lead Time (years)
Uprating (230 kV)	250,000 €/km	4
Uprating (138 kV)	150,000 €/km	4
DLR	6,000 €/km	2
BESS [17]	218 €/kWh	2
DSSC [9]	87 €/kVAr	1

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