Received: 9 November 2021 | Revised: 28 April 2022 | Accepted: 2 May 2022
DOI: 10.1002/er.8093

RESEARCH ARTICLE

INTERNATIONAL JOURNAL OF ENERGY RESEARCH WILEY

Resilient expansion planning of virtual power plant with an integrated energy system considering reliability criteria of lines and towers

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Funding information

Eesti Teadusagentuur, Grant/Award Number: PUTJD915

Summary

The portfolio of virtual power plants (VPP) is a flexible system for facilitating a wide range of resources with wide geographical coverage. A VPP can be placed at the intersection of electric power and energy systems by adding heat pumps to the portfolio, thereby accelerating the formation of integrated energy systems. VPPs, while virtual, still rely on a physical network for operations. The power transmission network has the responsibility of ensuring the security of supply, reliability of operation, and optimal planning for expansion. A vast majority of power network infrastructures, such as lines and towers, were installed in the last century, thus the existing infrastructure with aging components is not homogeneous. The transmission network covers a large geographical area which is expensive to maintain and requires large investments to avoid congestion. This work addresses the research question of how the condition of the existing network infrastructure affects the potential plans to expand the network. The condition of network infrastructure refers to the health of each line and tower. The decision of expansion includes both expansion with dismantling (restructuring) and without (reconfiguration) dismantling the existing lines and towers. The condition of the power network is determined by the maintenance cost of lines as well as a health index with associated risk factors of the tower. The investigation covers a range of cases where we research how the investment decisions change with the option of installing heat pumps in order to meet heating demand locally, and also when the condition of the network (health of lines and towers) is factored in, while also adding in the level of risk associated with each tower. Beyond the cases, extensive sensitivity analyses are conducted to evaluate the trade-offs between decision variables, such as cost of heat pump, coefficient of performance of heat pump, risk factors, and line and tower costs. The results of this work lay the foundation for understanding how the condition of network infrastructure impacts optimal decisions for expansion.

KEYWORDS
integrated energy systems, power system planning, virtual power plant

1 | INTRODUCTION

The United Nations projects that total carbon emissions need to be reduced by 7.6% annually for the coming decade in order to meet the Paris Agreement goal to keep the global temperature rise below 1.5°C.[1,2] In the power sector, a switch from conventional fossil fuels to renewable energy resources is rapidly underway as a means to cut down on emissions. This massive transition comes with challenges, including the planning and operation of the modern power and energy sector which consists of a large share of variable distributed energy resources.[3] As several studies indicate, sector coupling,[4] especially integrating the electricity and energy sectors, will lead to overall optimal energy systems and reductions in emissions.[5] An integrated energy system (IES) acts as a physical layer of interconnection between electric and heat systems and their flows. A virtual power plant (VPP) is the virtual layer on top of the physical layer that provides optimal management of assets in the overall network and market operations. A case study from Sweden demonstrates how a VPP can balance the variable renewable power generation.[6] An IES has the potential to provide not only flexibility in the overall system, but also minimization of losses by efficient utilization of resources and processes.[7] Renewable energy resources, such as solar and wind, are variable, uncertain and often distributed. To mitigate these challenges, massive energy storage solutions are required. Many large scale projects are currently underway and various energy storage technologies are being explored. In parallel, behind the meter, localized solutions and demand-side flexibility are two key solutions that are emerging as ways to maintain the supply-demand balance. A VPP enables pooling together decentralized and distributed generation, storage, and consumption into one platform.[8] Thereby a VPP forms a centralized, digital energy solution which can access energy and electricity markets with large geographical coverage.[9] VPPs are one among the widely adopted technologies for a distributed, decentralized and decarbonized power network.[10] The concepts of VPP and IES are explored in the literature. There is a study of the grid services provided by a VPP using IEC 61850 standard in Reference 11 and a conceptual analysis in Reference 12. Furthermore, authors in Reference 13 have proposed a hierarchical control strategy for VPP management for multiple grid support services. An optimal aggregation approach for VPP that considers network reconfiguration is presented by the authors.[14] A list of uncertainties associated with VPP and how to mitigate them is presented in Reference 15. In Reference 16, authors explore an energy-as-a-service business model through blockchain-based smart contracts in a VPP platform. It is evident from the available literature that a VPP with an IES has the potential to provide cost-effective and efficient solutions for total system planning and operations. However, very few studies address the VPP concept together with an IES to investigate how this coupling can contribute to mitigating the costly interventions in network expansion and reconfiguration within the VPP.

Shifting to a focus on technology, the power grid connects the bulk of generation to consumption, while maintaining overall system balance and stability. The power network is continuously expanding as demand grows and new sectors are being connected. It is reported by ACER (the European Union Agency for the Cooperation of Energy Regulators) that 136 billion euros have been invested in expanding transmission capacities across Europe to better the facilitation of the flow of electricity.[17] This power network also facilitates moving the distributed energy generation from the point of generation to the point of consumption. The system operator, therefore, must ensure the system's availability, stability, balance and security. The ageing of the network poses a threat to the resilient operation of the power system. The network requires continuous maintenance and supervision to function at optimal capacity. Several studies have been conducted to address how the system operator can ensure a resilient power supply as described in References 18,19. The condition of the network, specifically the condition of transmission towers and overhead lines, are often not among the decision variables in the models proposed in the existing literature. In fact, many expansion planning models are built on a top-down format, where the line capacities are aggregated, forming a representative network. This overlooks the practical condition of a particular network, which may have an adverse effect in real-world performance. The authors in Reference 20 elaborate on transmission tower failures under different scenarios, and there is also a study of a recent case in Texas, United States[21] where one ageing component lead to a transmission failure and a system blackout. A power network built in the last century cannot meet the requirements of the 21st century. The issue is not just transition of generation or responsive demand, but the transmission of power, be it long-distance or locally.

An investment planned without a proper insight into the condition of the network risks total or partial economic losses due to operational failures. When it comes to a VPP, system resiliency becomes an even bigger issue due to geographical coverage. The combination of a VPP with an IES presents multifold opportunities to make optimal techno-economic decisions. In order to fill the gap in the existing literature, this paper addresses how resilient power network expansion can be performed within an IES, including the representative conditions of the power network.

1.1 | Reasoning and challenges

Energy system integration refers to better linking the carrier, infrastructure, and end-user sectors. Energy system integration enables the reduction of greenhouse gases in the sectors where it is cumbersome to decarbonize. IES also reduces the total amount of energy required while increasing the efficiency of the overall system. Thereby IES aids in achieving better utilization of the resources. In addition, through system integration, the flexibility potential in the total system is unlocked. Heating demand both at a residential and industrial level represents a large portion of the energy demand. Heat demand is also a source of flexibility since the heating mechanism can maintain a comfortable temperature with less energy. Traditionally district heating or central heating is used across Europe. However, a central heating system not only incurs losses in transportation but is also difficult to control at the end-user level. Heat pumps on the other hand provide an economically viable and efficient solution to locally generate and control the heat while cutting down on transportation losses. To put into perspective in Europe heat represents 60% of total energy usage.[22] A significant emission reduction can be achieved through the transition to IES and deploying IES. The lack of knowledge and information on the return of long-term investment are among the key barriers for industries to shift towards such solutions. Adding a layer on the top, where a VPP accelerates digitalization of the power system while acting as a catalyst for the system integration, emission reduction, and efficiency. Arguably the price of electricity is highly influenced by the congestion in the power network. The transmission lines and towers are responsible for spatially distributing the bulk of the energy production. While the power network was built almost a century ago in most places, a significant expansion is taking place to electrify or trade electricity among regions. It is well understood that it is too expensive to modernize the whole network so instead the network is maintained with manual inspections in most places. In the studies in literature often this important factor is overlooked to simplify the problem formulation. This work aims to investigate and bring knowledge forward on the economic viability of network expansion and reconfiguration including the underlying condition of the network. Furthermore, this work postulates a scenario of VPP operating with an integrated energy system. The knowledge gap considered in this work is instrumental to determining optimal expansion planning for a long time horizon.

The system operator plans for network expansions at regular intervals to ensure optimal system operation and the proper integration of new generation units and/or demand within the network. Similarly, an asset owner performs regular maintenance to ensure the availability and performance of the generation asset. When planning new investments, the network operator needs to decide how to allocate the funds between network maintenance and capacity building. The network maintenance can be of two types: (a) restructuring – changing the structure of an existing network by dismantling existing lines and replacing them with new lines and scheduling maintenance of a line or a corridor that consists of multiple lines, and (b) reconfiguration – building new line capacity to facilitate new demand or generation units.[23] While network planning is a long-term and multi-horizon decision, the state of the network is dynamically changing in a short time horizon; therefore, the main objective of this work is to address multi-horizon network expansion while considering the dynamic deterioration of network conditions. In the literature, to the authors' best knowledge, this consideration is either absent or not addressed in the context of optimal expansion planning.

An estimation of online remaining useful life of power lines for predictive maintenance is presented in Reference 24. A condition monitoring method for wind turbines is discussed in Reference 25. An algorithm to facilitate localized energy exchanges through a VPP is presented in Reference 13. In Reference 13, authors present a decentralized provision algorithm to predict the renewable power production. A resilient system planning has the objective of ensuring the stability, balance, quality, safety and security of supply with demand. The scope of a VPP with an integrated energy system is widely studied in the literature, for instance: active dynamic aggregation model of VPP as an IES in Reference 26, operations for a regional IES-VPP in Reference 27, robust optimal dispatching method for multi-energy VPP in Reference 28, and a case study in China integrating regional IES to the central large scale IES in Reference 29. Authors in Reference 30 propose a joint expansion planning model with ownership sharing of the energy system and transmission grid. Authors in Reference 31 present a health index prediction method for overhead transmission lines. Automated utility pole condition monitoring is presented in Reference 32. An automatic condition assessment of high-voltage transmission lines using deep learning techniques is presented in Reference 33. An optimal aggregation approach for VPP considering network reconfiguration is presented by the authors Reference 14. A systematic review of optimal economic planning of power transmission lines is presented in Reference 34.

As the literature suggests, predictive and condition-based maintenance is being widely adopted by system operators and asset owners to schedule maintenance. Therefore, the condition of the network needs to be factored in decisions about expansion planning. In References 23,35, two mathematical optimization approaches for reliability-oriented expansion planning problems that consider restructuring and reconfiguration decisions are presented.

This paper focuses on modelling of VPP coupled with IES, from a network expansion perspective with inclusion of health indexes and risk factors associated with towers and power lines. The optimization problem is formulated from the network operator's perspective with perfect information. The VPP includes assets such as heat pumps, non-dispatchable generation units based on renewable resources with battery banks, and dispatchable generation units. The integrated energy system is formed by coupling the electric and heat demand at the residential level. The following subsections systematically explore the key challenges and research gaps addressed in this research work.

1.1.1 | The challenge of heat pump capacity allocation

A heat pump is considered a reliable and cost-optimal solution for mitigating local heating energy demand.[36] The coefficient of performance (COP) of a heat pump varies based on the underlying technology in the heat pump.[37] Authors in Reference 38 studied how the variable energy tariff levied on production can promote flexibility from heat pumps. The variation of COP reflects accordingly in the cost, specifically higher COP comes with a higher price. Determining optimal capacity installation of a heat pump depends on several factors, such as the COP of the heat pump, the cost of the heat pump, the condition of the network, etc. A relevant difficulty that arises is determining the optimal ratio of heat pump capacity to COP in order to meet the heat energy consumption needs and to mitigate costly intervention of network restructuring and reconfiguration. The size of the heat pump installation is a trade-off between the price of new heat pumps, the performance of new heat pumps, and the investment costs in new lines. Depending on the change in the market price, one decision might off-set another in terms of operational costs. Another factor is change in the consumption volume. If the volume of demand is likely to change in the coming decade, a mix of different energy resources might present a sustainable solution to meet the rising demand. However, the condition of the network would determine the optimal portfolio for cost effectiveness and technically feasibility. Upgrading the whole network is a demanding investment both technically and economically, which is typically not practical. Therefore this paper sets the objective of finding a balance between network interventions to maintain the condition with an optimal portfolio of integrated energy resources.

1.1.2 | The challenges of network condition

The expansion planning of the power network can be summarized into two parts: the condition of towers and the condition of lines. It is assumed that the associated power apparatus are part of the tower or line depending on where the apparatus is installed. In 2003 the biggest blackout in the US power system was caused because of imbalanced loading, resulting in sag, of transmission lines that have an estimated economic repercussion of $6 billion. A dynamic thermal rating (DTR) metric is used in the Institute of Electrical and Electronics Engineers (IEEE) standard 738-2012, to estimate the DTR values of EHV power lines.[39,40] In Reference 40, the authors have presented an investigation of utilizing IoT tools for real-time monitoring of the transmission lines. High temperature tolerant and low sag composite material-based conductors that can withstand up to 85°C are now available that could reduce the chances of sag formation. However, as the lines are getting loaded to their maximum capacity to match the demand the system operators face the challenge of determining how to balance the investment in upgrading to new overhead lines (OHL) and benefits to the overall network performance through optimally selecting the lines. Then authors in Reference 41 present a method to evaluate the optimal conductor type for a specific power network considering the material properties of the available OHL. A health index as introduced in Reference 31 is used for representing the health of towers. In addition to that, a risk factor associated with the region the tower is serving is also applied. The risk factor is essentially a weight metric that the system operator allocates depending on the specific consumer segment. A fragility curve metric is used in literature to determine the health of a transmission tower as described in References 42,43. The authors in the aforementioned research papers present a practical and real-world metric to measure the condition of the transmission tower using visual inspection.

Transmission lines in power networks are supported by towers, primarily for long distance power transmission. The longer the transmission line is, the higher the voltage and ground clearance level are. To maintain a safe tension in the transmission lines, a permissible limit of sag (line bending) is adopted. The age, wind, tower movement, and icing are among the primary factors that impact a sag formation.[44] Depending on the terrain the priority of the factors in influencing the OHL differs, such as mountains, hills, and forests, as the wind speed differs in the regions.

When the condition of transmission towers deteriorates, the transmission lines between the support towers bend and sag. This in turn lowers the line tension (vertical clearance), violating the effective ground clearance. Sag could also lead to horizontal clearance which is the distance between conductors and distance between conductor and structure. Excess sag leads to an increase in power losses and may also lead to a potential power failure. In addition, the amount of conduction needed to transfer the required amount of power also increases, as does the cost. Typically, the network operator resolves the aforementioned issue by re-instating the line tension by increasing the tower height (transmission level) or by stretching the line from both ends (distribution level).

To avoid this, an effective level of sag with vertical ground clearance[45] must be maintained. Additional transmission or support towers may also be needed to maintain the line levels if the condition of a certain tower has worsened. Effectively identifying the tower condition and maintaining its health would keep the power network safe and ensure an efficient power flow. Various transmission tower conditions through a health index are presented in Reference 33. In Reference 31, six classes of health indices are presented as a function of age and projected life span. Depending on the condition of the tower the health index varies from normal to critical.

In this work, a health index associated with lines and towers describing the condition of the network is adopted. A risk factor is bundled with the health index to describe the importance of a certain health index value. The risk factor varies between 0 and 1 while there are 6 classes of health indices.

1.2 | Key contributions and novelty

This paper expands the reliability-oriented network restructuring (RNR) model frameworks presented in References 23,35 to investigate resilient and optimal expansion planning of a virtual power plant with an integrated energy system. The key contribution of this work is both methodological and analytical. Indeed, this work focuses on proposing novel modelling features to include technological details of power and energy networks that have been overlooked in the literature, and to demonstrate their implications and the enhanced analyses that can be performed thanks to them, with a particular focus on virtual power plants. The novel modelling features refer to modelling the health of towers and the possibility of replacing nodes, as well as modelling the heat demand and the possibility to allocate new heat pump capacity. This allows a representation of a virtual power plant in an integrated electric and heat energy system through decentralized, dispatchable generation units and heat pump units. To the authors' knowledge, this is the first time that node replacements and health factors of towers are modelled in a way suitable for inclusion within multi-horizon mathematical optimization models for decision making within power network restructuring and reconfiguration for VVP-related applications. Therefore, this represents a new contribution on the methodological side. Regarding the heat pump, although modelling heat demand is not novel in itself, the possibility of analyzing the impact of new heat pump installation on the restructuring and reconfiguration decisions of a power network (in terms of line and tower replacements) has not been addressed in literature. Therefore, investigating the impact of heat pumps on the reliability-oriented network restructuring problem with a multi-horizon perspective is a new analytic contribution. In particular, on the analytical side, the novel modelling features contribute to understanding under which conditions heat pump installation and tower replacements become valuable for virtual power plants, given the costs involved in the power lines' restructuring, the degradation issues involved in the power lines' maintenance, and the risk issues involved in the towers' health conditions. Extensive sensitivity analyses are provided to investigate how a heat pump, as a local and behind-the-meter aggregated energy source, could balance the expensive operational costs and reduce high investments in network restructuring and reconfiguration, considering towers replacements, lines replacements, and new potential lines installation.

The novelty of the work is therefore summarized as follows:

- Methodological novelty
  - Novel modelling features to represent health factors of towers, nodal risk factors, and nodes replacement decisions in ways suitable for inclusion within reliability-oriented network restructuring optimization models for VPP applications.

- Analytical novelty
  - Extensive sensitivity analyses are performed to investigate the impact of new heat pump installation on the restructuring and reconfiguration decisions within VPP networks.
  - Extensive sensitivity analyses are performed to investigate the impact of health factors of tower and towers replacements on the restructuring and reconfiguration decisions within VPP networks.
  - Extensive sensitivity analyses are performed to investigate how the integration of VPP within energy systems can contribute to overcoming issues involved in the long-term degradation of power lines as well as risk-related issues involved in the deterioration of the tower's health conditions.

In summary, this work investigates the impact of resilient planning of power networks as a virtual power plant with integrated electric and heating energy system. Quantitative and qualitative findings are reported alongside the limitations of this current study. The following sections are organized as follows: Section 2 introduces the mathematical model, Section 3 presents the experiments and the findings and Section 4 draws conclusions with future works.

2 | METHODOLOGY

The main methodology adopted in this paper lies within the broad domain of Energy Informatics, with a focus on the key subject of smart energy and power systems modelling as discussed in Reference 46. This paper builds on the mathematical optimization models proposed in Reference 23,35. by including novel features that enhance the decision making process and expand the possibilities for sensitivity analyses. The novel modelling features refer to:

- Modelling the health of towers and the possibility of replacing nodes;
- Modelling the heat demand and the possibility of allocating new heat pump capacity.

The fundamental structure of the model remains the one proposed in Reference 23. Therefore, the modelling of network restructuring and reconfiguration, as well as line maintenance costs in a multi-horizon perspective and linearized power flow will not be discussed in this paper. The reader is invited to first familiarize herself with the modelling foundations proposed in Reference 23 to enhance understanding of the additional features proposed in this follow up paper. The nomenclature proposed in this paper is the same as the one proposed in Reference 23. Only additional constraints and modelling features will be discussed in this work, together with related additional variables and parameters. The constraints and features discussed in this paper work holistically with the constraints and features already thoroughly presented in Reference 23.

2.1 | Health of towers and node replacement decisions

As outlined in the previous sections, one relevant challenge in power networks is related to the condition of lines and towers. While the condition of lines has been thoroughly modelled and investigated in Reference 23, the condition of towers is a feature that is currently completely overlooked in literature when it comes to energy and power systems mathematical optimization models.

When studying a power network as a graph with arcs and nodes, we assume that arcs represent power lines, while nodes represent towers. If a tower's state of health degrades, this has an impact on the performance of the connected lines. If the tower condition is too poor, even a brand new line would not perform at its best, due to the negative impact that the connected tower may have on the line's properties. Therefore, a relevant trade-off arises between the need for replacing lines and the need for replacing towers. In graph theory, the need for replacing towers corresponds to the task of replacing nodes. To the best of the author's knowledge, there are no works in the literature that provide modelling formulations suitable for replacing nodes within mathematical optimization models, in order to tackle reliability oriented network restructuring issues of power systems.

A tower's state of health in a node i is identified by a new parameter V_i^{health}, while the decision to replace a tower in a node i is identified by a binary variable γ_i that is equal to 1 if a pole is replaced on node i, or zero otherwise.

A tower's replacement is tightly connected to decisions involving both existing and new lines. Existing lines can be kept as they are or replaced with new, better ones. In addition, new potential lines can be built between towers. This has been modelled in Reference 23. However, the performance of both existing lines and new lines is affected by the towers' state of health and by the decisions that involve potentially replacing towers.

The following paragraphs will outline how the towers' state of health and replacement can be modelled as a novel feature within Reference 23.

$$\gamma_i = 1 \Rightarrow p_{i,j,t,a} < = \overline{E}_{i,j}{}^{*} V_j^{health*}\left(1-\gamma_j\right) + \overline{E}_{i,j}{}^{*}\gamma_j \qquad \forall (i,j,t,a)\,|\,E_{i,j}=1; X_{i,j}=0 \tag{1}$$

$$\gamma_i = 0 \Rightarrow p_{i,j,t,a} < = \overline{E}_{i,j}{}^{*}\frac{V_i^{health}+V_j^{health*}}{2}\left(1-\gamma_j\right) + BigM^{*}\gamma_j \qquad \forall (i,j,t,a)\,|\,E_{i,j}=1; X_{i,j}=0 \tag{2}$$

Constraints 1 and 2 work for existing lines. They impose that, if a tower is not replaced, its state of health will penalize the capacity of line $\overline{E}_{i,j}$ that is connected to the tower. In particular, given a power line represented by an arc $i-j$, if a tower on node i is replaced, but a tower on node j is not replaced, then the line capacity is penalized by the tower's state of health j (constraint 1).

The same constraint 1 can be rewritten by swapping i and j. This way the mirroring condition is imposed: if a tower on node i is not replaced and a tower on node j is replaced, the line capacity is penalized by the state of health of the tower on node i.

If a tower on node i is not replaced and also a tower on node j is not replaced, the line capacity is penalized by the average value of the health of the two towers (constraint 2). This latter condition assumes that an average value of the towers' health can be utilized to penalize line capacity. Of course, more refined representations can be utilized in the model if industrial real-world expertise suggests different health functions involving more than one tower.

The proposed equations have been modelled using indicator constraints. A similar approach to if-then formulations has been successfully used also in Reference 47,48. For further reading about handling indicator constraints in mixed integer problems see Reference 49.

$$\begin{aligned}\gamma_i = 1 \Rightarrow p_{i,j,t,a} < = \; & \overline{E}_{i,j}{}^{*}\left(1-\sum_{c,a1=1}^{a1=a-Z-1} k_{i,j,c,a1}\right)\\ & +\left(\sum_{c,a1=1}^{a1=a-Z-1} k_{i,j,c,a1}{}^{*}\overline{N}_c\right) * V_j^{health*}\left(1-\gamma_j\right)\\ & +\left(\sum_{c,a1=1}^{a1=a-Z-1} k_{i,j,c,a1}{}^{*}\overline{N}_c\right) * \gamma_j\\ & \forall (i,j,t,a)\,|\,E_{i,j}=1; X_{i,j}=1\end{aligned} \tag{3}$$

$$\begin{aligned}\gamma_i = 0 \Rightarrow p_{i,j,t,a} < = \; & \overline{E}_{i,j}{}^{*}\left(1-\sum_{c,a1=1}^{a1=a-Z-1} k_{i,j,c,a1}\right)\\ & +\left(\sum_{c,a1=1}^{a1=a-Z-1} k_{i,j,c,a1}{}^{*}\overline{N}_c\right) * \frac{V_i^{health}+V_j^{health*}}{2}\left(1-\gamma_j\right)\\ & +\left(\sum_{c,a1=1}^{a1=a-Z-1} k_{i,j,c,a1}{}^{*}\overline{N}_c\right) * BigM^{*}\gamma_j\\ & \forall (i,j,t,a)\,|\,E_{i,j}=1; X_{i,j}=1\end{aligned} \tag{4}$$

Constraint 3 handles the towers' replacement when restructuring decisions are also involved.

Here $p_{i,j,t,a}$ represents the power flow in each line, $\overline{E}_{i,j}$ is the capacity of the existing line, $\overline{N}_c$ is the capacity of a new type of line, and γ_i is the binary variable equal to 1 if an existing pole is replaced with a new one, 0 otherwise. Another binary variable is introduced $k_{i,j,c,a}$, equal to 1 if an existing arc i, j is replaced by a new cable, 0 otherwise. As already outlined earlier, a tower's state of health in a node i is identified by the parameter V_i^{health}.

If a tower on node i is replaced and a tower on node j is not replaced, then not only the capacity of the existing lines is penalized, but also the capacity of the new lines (that may be installed to replace existing obsolete lines) are penalized by the tower's state of health on node j. This means that, if an existing line is replaced by a new line ($k_{i,j,c,a} = 1$), then the capacity of the existing line is penalized for the years that come before the beginning of construction, while the capacity of the new line is penalized for the years that come after the construction.

The same constraint 3 can be rewritten by swapping i and j. This way the mirroring condition is imposed if a tower on node i is not replaced and a tower on node j is replaced.

Constraint 4 handles the towers' replacement when restructuring decisions are involved and when both towers on node i and j are not replaced. Again, this condition assumes that an average value of the towers' health can be utilized to penalize line capacity. The new constraints handle the penalization of existing lines before the time of construction and the penalization of new lines which replace existing lines after the time of construction.

The constraints proposed in 3 and 4 are non-linear since they involve the product of two binary decision variables $k_{i,j,c,a}$ and γ_j. Such constraints have been properly linearized by creating a new binary variable $\mu_{i,j,t,a} = k_{i,j,c,a} * \gamma_j$ and by including three inequalities in the form of:

$$\mu_{i,j,t,a} \le k_{i,j,c,a} \tag{5}$$

$$\mu_{i,j,t,a} \le \gamma_j \tag{6}$$

$$\mu_{i,j,t,a} \geq k_{i,j,c,a} + \gamma_j - 1 \tag{7}$$

The new binary variable $\mu_{i,j,t,a}$ can then be used inside the non-linear constraints to replace the product of the binary variables $k_{i,j,c,a}$ and γ_j. Of course, each constraint has to be linearized individually.

$$\gamma_i = 1 \Rightarrow p_{i,j,t,a} < = \left(\sum_{c,a1=1}^{a1=a-Z-1} y_{i,j,c,a1}{}^{*}\overline{N}_c \right) * V_j^{health*} \left(1-\gamma_j\right) + \left(\sum_{c,a1=1}^{a1=a-Z-1} y_{i,j,c,a1}{}^{*}\overline{N}_c \right) * \gamma_j \quad \forall (i,j,t,a) \mid N_{i,j}^{pot} = 1 \tag{8}$$

$$\gamma_i = 0 \Rightarrow p_{i,j,t,a} < = \left(\sum_{c,a1=1}^{a1=a-Z-1} y_{i,j,c,a1}{}^{*}\overline{N}_c \right) * \frac{V_i^{health} + V_j^{health*}}{2} \left(1-\gamma_j\right) + \left(\sum_{c,a1=1}^{a1=a-Z-1} y_{i,j,c,a1}{}^{*}\overline{N}_c \right) * \gamma_j{}^{*} BigM \quad \forall (i,j,t,a) \mid N_{i,j}^{pot} = 1 \tag{9}$$

Constraints (8) and (9), (10), (11) handle the towers' replacement when new potential installations are involved. They work similarly to the constraints presented for the restructuring decisions, hence the same considerations from the previous paragraphs regarding linearization and indicator constraints apply. In order to model the choices of potential installations of new lines, the binary variable $y_{i,j,c,a}$ is included. It is equal to 1 if a potential arc is created between nodes i and j, 0 otherwise.

In addition to the constraints proposed above, decisions concerning tower replacements also affect objective function and investment costs. In particular, a new term of cost is created as follows:

$$\sum_i V^{CRF*} \gamma_i{}^{*} V^{cost} \tag{10}$$

where γ_i is the binary decision variable for new towers installation, V^{cost} is the installation cost of new towers, and V^{CRF} is the capital recovery factor to actualize investments in new towers. The latter is defined as:

$$\frac{r^{*}(1+r)^{V^{life}}}{(1+r)^{V^{life}} - 1} \tag{11}$$

2.2 | Handling heat demand

Compared to the work presented in Reference 23, this paper aims at a more detailed representation of the final demand by considering two separate aggregated demand curves at each node: thermal demand and electrical demand. The aggregated thermal demand for residential areas refers mainly to low temperature demand for space heating and water heating (specifically room heating, snow melting, floor heating, shower heating). For industrial areas we refer mainly to high temperature demand for process heat in industry. For this aggregated electrical demand, we refer mainly to loads, such as heating or cooling loads through air conditioning, power appliances (ie, computers, refrigerators, televisions, fans, lighting load, etc.), and electric vehicle charging. The thermal demand can be met in two main ways: traditional heating systems (namely boilers, district heating, wood/pellets burning) and power-to-heat technologies. The latter refers to the conversion of electrical energy to heat, and the main technology here is currently represented by heat pumps. Flexible heat pumps are an important aspect of flexibility due to their higher efficiency when compared to traditional electric resistive heaters. This means their integration can be key to fulfilling an increased portion of energy demand without the need for expensive network reinforcement. This paper introduces an analysis of the decision for new heat pump installations to fulfill part of the heating demand. This includes looking at ways in which heat pumps can bring added flexibility to the system and lower the investments in network restructuring and reconfiguration. Looking at future projections of increased energy demand, we aim to understand which portion of heat demand should be satisfied with a power-to-heat technology (heat pump) in order to minimize the overall costs of network restructuring and reconfiguration.

$$f_{i,t,a}^{in} = D_{i,t,a} + d_{i,t,a}^{heat01} + \frac{d_{i,t,a}^{heat02}}{COP} \quad \forall (i,t,a) \tag{12}$$

$$d_{i,t,a}^{heat01} + d_{i,t,a}^{heat02} = D_{i,t,a}^{heat} \quad \forall (i,t,a) \tag{13}$$

$$d_{i,t,a}^{heat02} < = \sum_{a1=1}^{a1=a} h_{i,a1} \quad \forall (i,t,a) \tag{14}$$

Constraint (12) defines the power balance in each node. The left side of the constraint summarizes the power flow into the node through the term $f_{i,t,a}^{in}$. This term is split and thoroughly described in Reference 23 and the left side of this constraint remains the same as the one proposed in Reference 23. The right side of the constraint is different, as the demand curves are now split into two: power demand $D_{i,t,a}$ and heat demand. The latter is further split into the portion of heat demand that can be met by traditional hating systems $d_{i,t,a}^{heat01}$ and the portion of heat demand that can be met through a heat pump $d_{i,t,a}^{heat02}$. The latter is divided by the heat pump coefficient of performance COP which can be changed to allow sensitivity analyses during computational experiments. Both $d_{i,t,a}^{heat01}$ and $d_{i,t,a}^{heat02}$ are decision variables, so the model produces an optimal decision for much heat demand is worth satisfying with existing traditional heating systems and how much heat demand is worth satisfying with new, aggregated heat pump installation in that particular node.

Constraint (13) defines the total heat demand curve as the summation of the heat demand that is satisfied using existing traditional heating systems and the heat demand that is satisfied by installing new heat pump capacity.

Constraint (14) keeps track of the heat pump aggregated capacity installation in each node and for each strategic year. For each strategic year, the heat pump capacity in a node is given by the heat pump installed in the previous years, plus the capacity installed in the current year. Here $h_{i,a}$ is the new aggregated heat pump capacity installed on a node i in a certain year a. The portion of heat demand satisfied by heat pumps should not exceed the available installed capacity.

Finally, an additional term in the objective function must be added to include the investment costs in new heat pump capacity installation. Again, the capital recovery factor is used and the related formula is given in the following Equation (15) where H^{CRF} is the capital recovery factor of a heat pump, $h_{i,a}$ is the decision variable related to the installed heat pump capacity, H^{cost} is the unitary cost of a heat pump.

$$\sum_{i,a} H^{CRF*} h_{i,a}{}^{*} H^{cost} \tag{15}$$

The capital recovery factor of a heat pump depends on the r rate r and on the heat pump average life H^{life} and it is calculated as in Equation (16).

$$\frac{r^{*}(1+r)^{H^{life}}}{(1+r)^{H^{life}}-1} \tag{16}$$

2.3 | Introducing a risk factor

A risk factor is introduced in the mathematical optimization model to prioritize investments in areas that are considered more critical for the power system companies. The fundamental idea behind a risk factor is that areas with a high risk have a higher priority for the power system company, and therefore tighter constraints in terms of meeting the existing and new forecast demand. Lower risk areas have a lower priority for the power system company, which would allow relaxing the constraints in terms of meeting the existing and new forecast demand, by allowing for some demand not met. This will of course affect the decisions in terms of lines restructuring and reconfiguration as well as pole replacement, since low risk areas can still be connected to obsolete lines or towers, allowing for a portion of demand not to be met. The risk factor changes over the years, as the priority of a certain nodes can increase or decrease in the future. For instance, if a new district is planned in a node that is currently not highly populated, the priority of that particular node may increase in the forthcoming years once the district is fully developed. If an area changes its features or if the population is gradually moving out, the priority for that particular node may decrease in the forthcoming years.

The risk factor is included in the model by using a risk parameter $V_{i,a}^{risk}$ in the power flow equation as shown in Equation (17). It appears in the model as a percentage applied to the total demand in the node.

$$f_{i,t,a}^{in} = \left(D_{i,t,a} + d_{i,t,a}^{heat01} + \frac{d_{i,t,a}^{heat02}}{COP} \right) * V_{i,a}^{risk} \qquad \forall (i,t,a) \tag{17}$$

However, it should be highlighted that the risk factor is much more than just a single number, and that there is a whole set of qualitative and quantitative analyses that have to be performed to properly define it. In particular, the following definition of risk factor applies:

$$V_{i,a}^{risk} = f\Big[\left(F_{1,c}^{ex}, F_{2,c}^{ex}, \ldots F_{n,c}^{ex}\right); \left(F_{1,c}^{in}, F_{2,c}^{in}, \ldots F_{n,c}^{in}\right); \left(F_{1,x}^{ex}, F_{2,x}^{ex}, \ldots F_{n,x}^{ex}\right); \left(F_{1,x}^{in}, F_{2,x}^{in}, \ldots F_{n,x}^{in}\right)\Big] \tag{18}$$

where the risk factor is a function of different factors as follows:

- $F_{1,c}^{ex}, F_{2,c}^{ex}, \ldots F_{n,c}^{ex}$ is a function of external controllable factors;
- $F_{1,c}^{in}, F_{2,c}^{in}, \ldots F_{n,c}^{in}$ is a function of internal controllable factors;
- $F_{1,x}^{ex}, F_{2,x}^{ex}, \ldots F_{n,x}^{ex}$ is a function of external non controllable factors;
- $F_{1,x}^{in}, F_{2,x}^{in}, \ldots F_{n,x}^{in}$ is a function of internal non controllable factors.

The above definition explains that the risk is a function of different factors F that affect the overall classification of a certain area. Examples of such factors are for instance the terrain, the number of consumers, the type of consumers, the seasonality of consumers' availability (ie, if consumers are present throughout the year or just in winter or summer), the future projections for regional development (ie, future demand projections and future projections in terms of new infrastructures development), type of nature that characterizes a node (ie, if a node is surrounded by a forest it may be difficult to reach), distance from water, and weather patterns (ie, length and harshness of certain seasons such as winter or summer). The factors affecting the conditions of power networks can be broadly classified into two types: controllable and uncontrollable. While both can be monitored, controllable factors can be fully altered while uncontrollable factors can only be slowed down. For example, a sag formation on the overhead transmission line can be classified as a controllable factor as it can be altered by tightening the lines and increasing the tower height. A material deterioration of a transmission line, on the other hand, cannot be controlled as it is a natural degrading process. Factors can be also classified as internal or external based on the reason for an issue. For example, an over-voltage issue can be an external fault that might be caused by high share of renewable energy. This can be classified as an internal fault if adequate voltage support was not planned by the responsible system operator in the region. Note that the internal and external classification is tightly linked to the cause of a factor (namely, why it happened) while the controllable and uncontrollable classification is tightly linked to the effect of it (namely, what can be done about it).

Each factor in 18 can be then multiplied by a weight *W* that defines how important that particular factor is for that particular area and also incorporates information about the probability of the occurrence of that factor. So that Equation (18) is further expanded into Equation (19) as follows:

$$V_{i,a}^{risk} = f\left[\left(F_{1,c}^{ex\,*} W_{1,c}^{ex}, F_{2,c}^{ex\,*} W_{2,c}^{ex}, \ldots F_{n,c}^{ex\,*} W_{n,c}^{ex}\right); \left(F_{1,c}^{in\,*} W_{1,c}^{in}, F_{2,c}^{in} {*}_{2,c}^{in}, \ldots F_{n,c}^{in\,*} W_{n,c}^{in}\right); \left(F_{1,x}^{ex\,*} W_{1,x}^{ex}, F_{2,x}^{ex\,*} W_{2,x}^{ex}, \ldots F_{n,x}^{ex\,*} W_{n,x}^{ex}\right); \left(F_{1,x}^{in\,*} W_{1,x}^{in}, F_{2,x}^{in\,*} W_{2,x}^{in}, \ldots F_{n,x}^{in\,*} W_{n,x}^{in}\right)\right] \tag{19}$$

This is mainly done at a qualitative level by industrial experts.

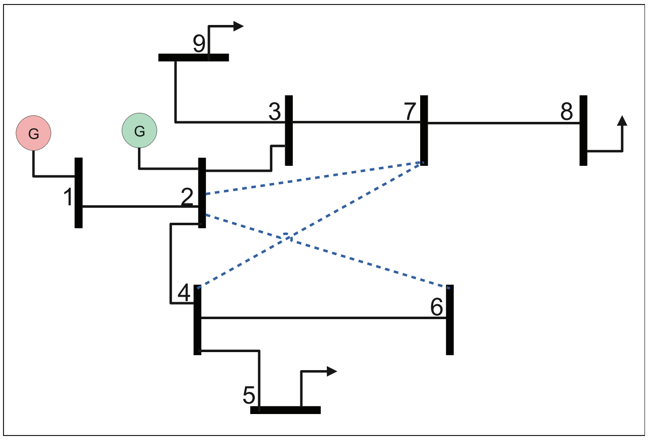


FIGURE 1 Power network configuration used for computational experiments

3 | EXPERIMENTS AND FINDINGS

Computational experiments are performed using the proposed model to investigate how network condition impacts the decision to expand network capacity with an integrated energy system. Afterwards sensitivity analyses are conducted to illustrate the trade-offs between potential investments in new generation units, heat pump units, network restructuring with lines replacements, and reconfiguration decisions with the dismantling of lines, and replacement of towers.

The VPP and the assets are reflected through an aggregated network. For this purpose, a modified IEEE-9 bus system is used as the base VPP network for running the computational experiments – see Figure 1. This network is constructed in a way that it has both non-dispatchable and dispatchable generation units, as is typically observed in the portfolio of a VPP. Realistic data of production and consumption received from the utility industries are used to run the tests; therefore, the construct and data-set closely resemble the real-world setting. The data-set comes with non-disclosure restrictions due to the privacy, commercial interests, ethical and security concerns, which makes it challenging for research publications.

The prototype of the proposed mathematical optimization model is developed using the AIMMS modeling platform.[50] AIMMS provides a versatile platform for rapidly building and testing mathematical optimization models. The model is solved using the branch-and-bound algorithm of the CPLEX solver (as well as its modern features, like cutting planes and heuristics) from IBM ILOG,[51] which is a high-performance solver for mixed integer programming problems like the one proposed in this paper. The experiments presented in the paper are conducted using a personal computer with a 3 Ghz processor and 32GB RAM.

3.1 | Structure of the experiments

The network configuration presented in Figure 1 consists of 9 nodes and 10 arcs. The network is represented at an aggregated level, meaning each node is representative of a group of buildings, each path formed by one or more arcs represents a corridor, and a group of arcs and nodes form a zone. The network has both conventional and renewable generation units where a typical off-shore wind turbine production curve is used as the basis for renewable production. The energy consumption in electric and heating demand are presented separately. The planning horizon is assumed to be a decade, given that network reconfiguration decisions would typically fall within this period. In addition, significant technological changes affecting the unitary cost and consumption trends and patterns could also be observed within this period. The construction time for lines and towers are set to a three-year period, which is the maximum period for the construction process under normal conditions. All data are scaled to inherit patterns and trends while preserving the privacy and commercial interests.

A conventional generator of sufficient capacity to meet the grid's total load is present in node 1. A variable renewable generation unit, specifically offshore wind turbines, is present in node 2, along with a battery bank. Linearly increasing electric and heat demand are located in node 5, 8, and 9. The total energy demand at node 8 would surpass the line capacities on year 6. The aforementioned assumptions are detailed in a previous paper from the authors in Reference 23. To reflect the real world choices, the model was given two options, C1 and C2, to choose from when it comes to lines replacement. One of them, C1, is higher capacity and more expensive than the other.

The following subsections detail the sensitivity analyses for each feature of the model. Every figure includes a set of tables illustrating the decision variables in focus. The decision variables include: reconfiguration through new line installation, restructuring through replacement of existing lines and transmission towers, total investment and operational costs, and new capacity building through renewable generation unit or heat pump installations. The analyses are meant to understand the effect of various components on the decision variables. The findings focus on the ratio between the level of impact and a range of variations in a component. Together the experiments and findings generalize and broaden the understanding of the implications of technology, demand and cost.

3.1.1 | Map of components and challenges

Small scale non-dispatchable generation assets such as wind turbines and solar panels can be treated as behind-the-meter solutions. A portion of the electric demand is met locally when these assets are active, while the larger share of demand is sourced from the power grid. Small to medium scale micro-injections of non-dispatchable energy generation to the power grid are considered trivial in terms of volume of power supply. Medium to large scale generation assets such as the off-shore wind turbines have a stable generation curve and smaller storage requirement. To identify the impact of investment in heat pump installations, the experiments are broadly classified into “with” and “without,” referring to the presence of existing non-dispatchable renewable power generation assets or the lack thereof. A series of experiments are conducted for each category: COP test, heat pump cost with line cost, COP with heat pump cost, and increasing and decreasing trends of heating demand. Every experiment begins with a base case, accompanied with sensitivity analyses to present the changes.

In the following tables we refer to a potential new installation as restructuring tasks.

3.1.2 | Applicability and validation

The IEEE-9 system is considered for testing and validation purposes. However, each arc in the graph can also be thought of as an aggregated representation of a larger corridor. As a result, by aggregating corridors according to various zonal attributes and clustering algorithms, any small IEEE test system can also be utilized to refer to more complicated systems. Furthermore, supercomputing and cluster computing can be used to handle the computational challenges of large-scale instances. UNINETT Sigma2, the Norwegian e-infrastructure for Research and Education, is an example of such infrastructure, as it provides high-performance computing and large-scale data storage services to individuals and groups involved in research and education at all Norwegian universities and colleges, as well as for other publicly funded organizations and projects. Another example is the HPC lab, which may be found at Solstorm.iot.ntnu.no (HPC standing for High Performance Computing at the NTNU lab for Computational Economics and Optimization). Large-scale mathematical optimization has already been effectively implemented and solved with such infrastructures.[47,52]

It is also important to highlight the strategic nature of the problem that is being investigated. This problem does not involve a real-time decision making process, but rather, it is a long term analyses of the best restructuring and reconfiguration decisions that takes into account different long term factors of power systems. As a result, computational time is not the main issue here, as a company would be willing to wait hours, or even few days, to have the opportunity to look into an optimal solution that could contribute to saving huge amounts of money not only now, but also throughout the years ahead. In addition, parallel and distributed computing, as well as decomposition techniques or time-series aggregation techniques[53] can be investigated to study larger instances of the problem. However, addressing scalability issues of large-scale mathematical optimization models is outside the scope of this work. This work focuses rather on proposing novel modelling features that include technological details of power and energy networks that have been overlooked in the literature and demonstrates how their inclusion has important implications for performing enhanced analyses. For this purpose, a theoretical analyses and experimental validation with an IEEE-9 system is given priority over larger case studies. There are several reasons to justify the practicality and utility of the chosen experimental validation approach. Experimental validation is suggested as a proper way to validate a model in Reference 54.

According to the authors, such an approach entails the collection of raw data in order to generate experimental data. Experimental data can be turned into experimental “features” if necessary. The technique that has been adopted for the proposed case studies is the generation and utilization of experimental data within a smaller test case for model validation. Indeed, “the validation procedure becomes one of determining the model's usefulness for the intended application(s) and/or the range of applications for which the model is valid,” according to Reference 55.

Validation and verification might be theoretical, experimental, or based on real-world examples. Each one has its own set of benefits and drawbacks. Real-world examples such as those presented in Reference 56 have the benefit of being grounded in “lived reality,” but they have the drawback of falling under the scalability issues. The approach taken in this paper can be classified under the so-called “validation by construct approach,” which entails “conceptualization of a problem based on experience, precedent (other models or writing), and theory, and the specification of data for the problem using reasonable scientific estimation,” as discussed in Reference 55.

Accordingly, the dataset for the suggested case studies was derived from real-world observations of real-world power systems firms. As a result, the examples presented are not actual and wide, but they are realistic enough to be used in a validation by construct approach through various sensitivity analyses, providing a wider range of smaller examples. Nevertheless, the authors acknowledge the need for a comparative analysis based on larger real network data-set which will be available in a separate, full-length paper in future studies. Finally, the validation by construct approach suggested in the paper remains a valuable contribution that has been incorporated in a number of cited papers in the literature, including.[48,57-60]

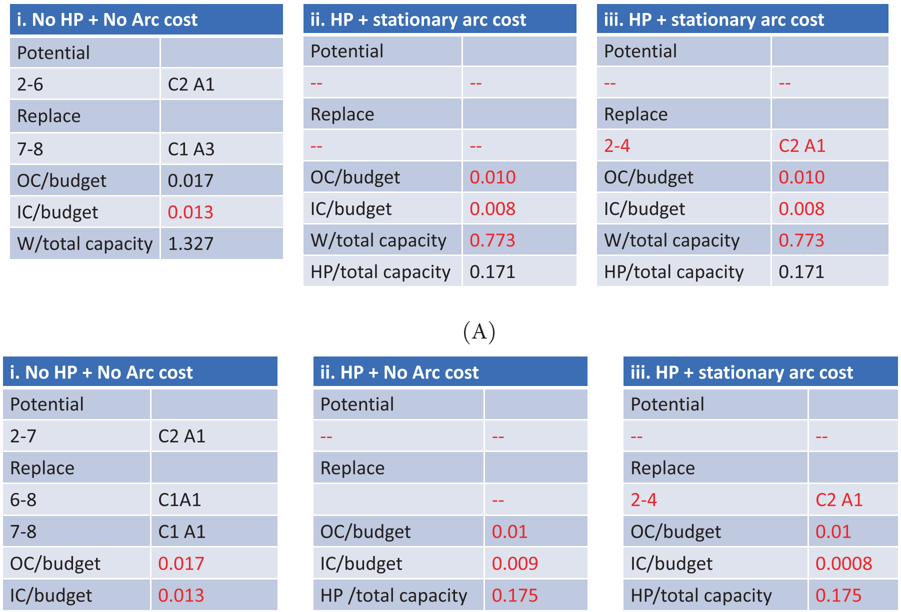
3.2 | Network interventions with impact of heat pump

Figure 2A presents the model decisions with and without a non-dispatchable generation unit. Every table lists the decision variables associated with the case. The conditions of the test are explained in the table titles. The heating demand at node 8 is projected to surpass the existing line capacities in arcs 7-8 and 6-8 in the sixth year. This creates congestion in the network, as outlined in the previous section. Therefore, reconfiguration and restructuring decisions are observed.

The underlying assumptions for the set of experiments presented in Figure 2A are: no maintenance cost of lines and no heat pumps available.

Without the availability of a heat pump, both reconfiguration (2-6) and restructuring (7-8) decisions are made in order to meet demand. When a heat pump option is available among the potential optimal decisions, heat pumps are installed in place of any network interventions because the performance with a heat pump is better than traditional electricity to heat conversion. This results in a 39% decrease in the operational cost and a 35% increase in the investment cost. When the cost to maintain existing lines 2-4 is taken into consideration, then there is a change in the investment schedule, where line 2-4 is restructured. Comparing table a.iii with table a.i of Figure 2A it is possible to note that the new cable replacement in table a.iii is accompanied by no potential installations that we see in table a.i. This is because the possibility of installing heat pumps is preferred over building new line capacities.

Figure 2B shows the decisions when additional non-dispatchable generation units are not available. Without an option to invest in heat pump units (see table b.i), the optimal decisions are reconfiguration (2-7) or



i. No HP + No Arc cost	
Potential	
2-6	C2 A1
Replace	
7-8	C1 A3
OC/budget	0.017
IC/budget	0.013
W/total capacity	1.327

ii. HP + stationary arc cost	
Potential	
--	--
Replace	
--	--
OC/budget	0.010
IC/budget	0.008
W/total capacity	0.773
HP/total capacity	0.171

iii. HP + stationary arc cost	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.010
IC/budget	0.008
W/total capacity	0.773
HP/total capacity	0.171

(A)

i. No HP + No Arc cost	
Potential	
2-7	C2 A1
Replace	
6-8	C1A1
7-8	C1 A1
OC/budget	0.017
IC/budget	0.013

ii. HP + No Arc cost	
Potential	
--	--
Replace	
	--
OC/budget	0.01
IC/budget	0.009
HP /total capacity	0.175

iii. HP + stationary arc cost	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.01
IC/budget	0.0008
HP/total capacity	0.175

(B)

FIGURE 2 Restructuring decisions when heat pump is available. (A) With non-dispatchable power generation units. (B) Without non-dispatchable power generation units

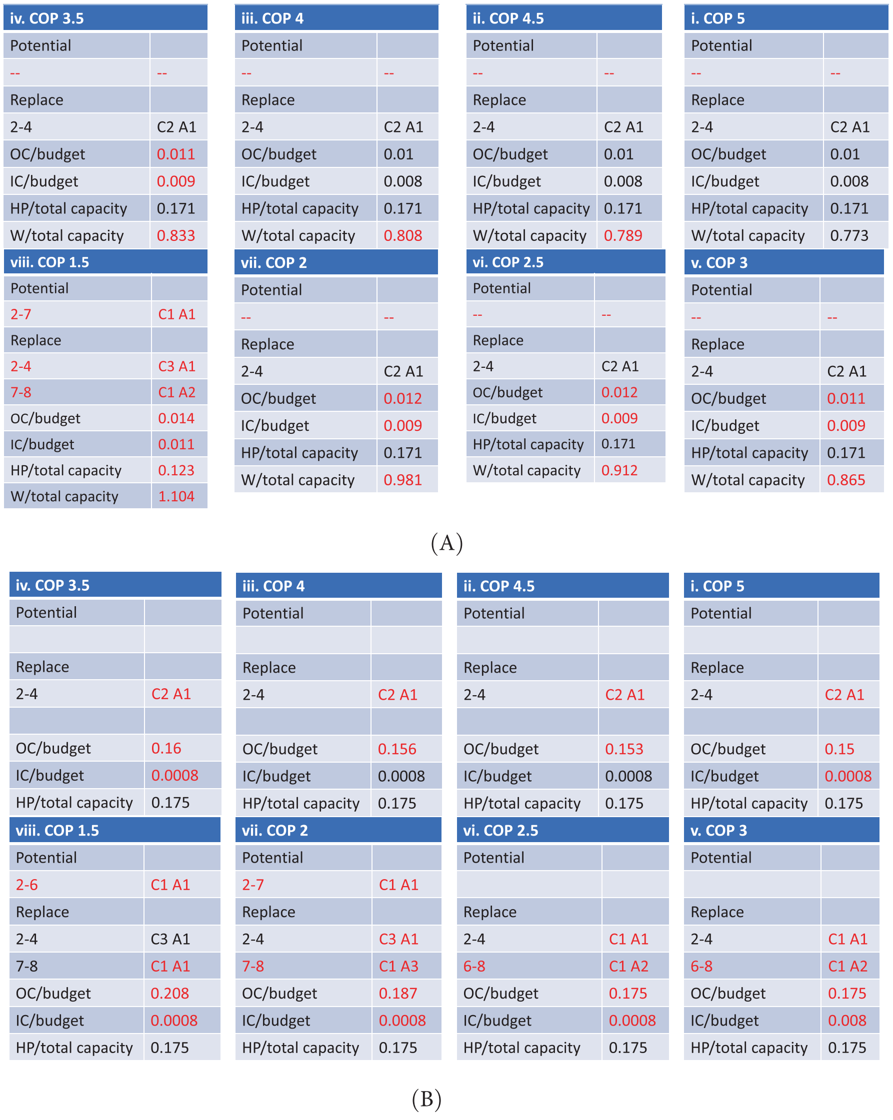
restructuring (6-8, 7-8). No network interventions are observed when a heat pump is available (see table b.ii). Comparing both the previous instances, there is a 39% increase in operational costs and a 33.8% decrease in investment costs with investments in heat pump units. The reason is that the heat pump availability helps avoid costly investments in network interventions. With the inclusion of stationary maintenance costs in arc 2-4, a network intervention decision is taken in the form of restructuring (2-4). It can be observed that with investment in heat pumps as an option, the number and mode of network interventions are significantly reduced, even when the maintenance cost of lines comes into the picture. The investment costs increase while the operational costs decrease.

3.2.1 | COP test

The coefficient of performance of a heat pump is an efficiency metric ranging from 5 to 1.5, depending on technology and other environmental factors.[61,62] In Reference 38, the authors highlight that a COP of 3.5 becomes competitive in spot electricity market prices. Figure 3 shows a sensitivity analysis of the coefficient of performance with and without non-dispatchable generation units. By gradually decreasing the COP by 10%, it is apparent how the decision changes in terms of network interventions and costs.

Comparing the decision changes in both cases, it can be observed that the case without non-dispatchable generation units has more network interventions with a decrease in the COP. From COP 2.5 to 2, for instance, results in additional network interventions through reconfiguration (2-7) and restructuring (6-8). Similar network interventions, in the case of existing non-dispatchable generation units, are observed from COP 2 to 1.5. This leads to the observation that non-dispatchable generation units introduce additional decision flexibility.

While the cumulative sum of heat pumps installed over a 10-year time horizon remains the same in most of the cases, it was observed that the rate of capacity building over the years is significantly different compared to network interventions. The changes in new heat pump capacities are highlighted in red. When the COP is assumed to be as low as 1.5, it can be observed that this is the only case when the cumulative capacity of heat pump installation is lower than the other cases. Figure 4 details the cost curves for both cases, matching the change in cost between two consecutive COP variations. Comparing the investment cost curves ic1 and ic2, while ic1 is linearly increasing, ic2 is relatively stable with a breakthrough at COP 3. This means that at COP 3 and beyond, the HP becomes an optimal option for investment compared to network interventions. Indeed, after COP 3 the change in investment with consecutive increments in COP values remains the same. The same trend can be also observed with operational costs (oc1 and oc2). This change is due to the change in the efficiency of the heat pump while no flexibility is added from the non-dispatchable generation units.



(A)

iv. COP 3.5	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.011
IC/budget	0.009
HP/total capacity	0.171
W/total capacity	0.833

iii. COP 4	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.01
IC/budget	0.008
HP/total capacity	0.171
W/total capacity	0.808

ii. COP 4.5	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.01
IC/budget	0.008
HP/total capacity	0.171
W/total capacity	0.789

i. COP 5	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.01
IC/budget	0.008
HP/total capacity	0.171
W/total capacity	0.773

viii. COP 1.5	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A2
OC/budget	0.014
IC/budget	0.011
HP/total capacity	0.123
W/total capacity	1.104

vii. COP 2	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.171
W/total capacity	0.981

vi. COP 2.5	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.171
W/total capacity	0.912

v. COP 3	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.011
IC/budget	0.009
HP/total capacity	0.171
W/total capacity	0.865

(B)

iv. COP 3.5	
Potential	
Replace	
2-4	C2 A1
OC/budget	0.16
IC/budget	0.0008
HP/total capacity	0.175

iii. COP 4	
Potential	
Replace	
2-4	C2 A1
OC/budget	0.156
IC/budget	0.0008
HP/total capacity	0.175

ii. COP 4.5	
Potential	
Replace	
2-4	C2 A1
OC/budget	0.153
IC/budget	0.0008
HP/total capacity	0.175

i. COP 5	
Potential	
Replace	
2-4	C2 A1
OC/budget	0.15
IC/budget	0.0008
HP/total capacity	0.175

viii. COP 1.5	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.208
IC/budget	0.0008
HP/total capacity	0.175

vii. COP 2	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A3
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vi. COP 2.5	
Potential	
Replace	
2-4	C1 A1
6-8	C1 A2
OC/budget	0.175
IC/budget	0.0008
HP/total capacity	0.175

v. COP 3	
Potential	
Replace	
2-4	C1 A1
6-8	C1 A2
OC/budget	0.175
IC/budget	0.008
HP/total capacity	0.175

FIGURE 3 Restructuring decisions with various coefficient of performance of heat pump. (A) With non-dispatchable power generation units. (B) Without non-dispatchable power generation units

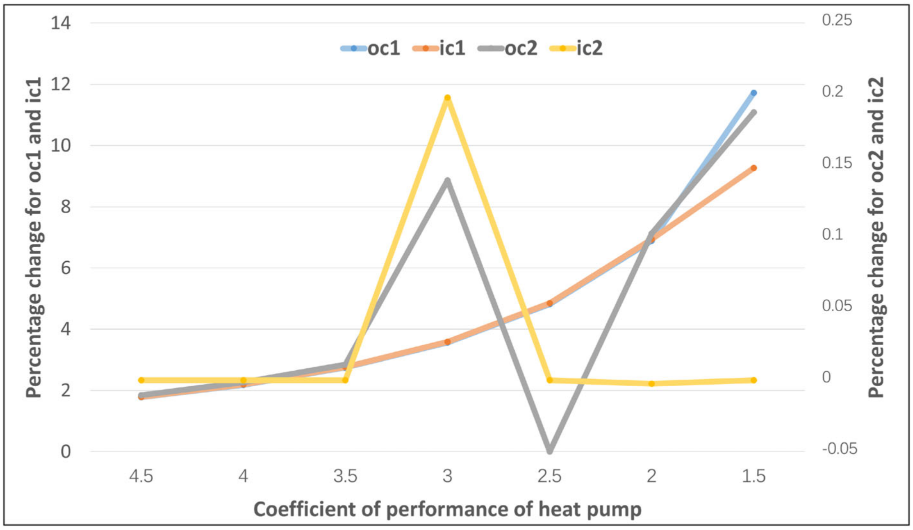
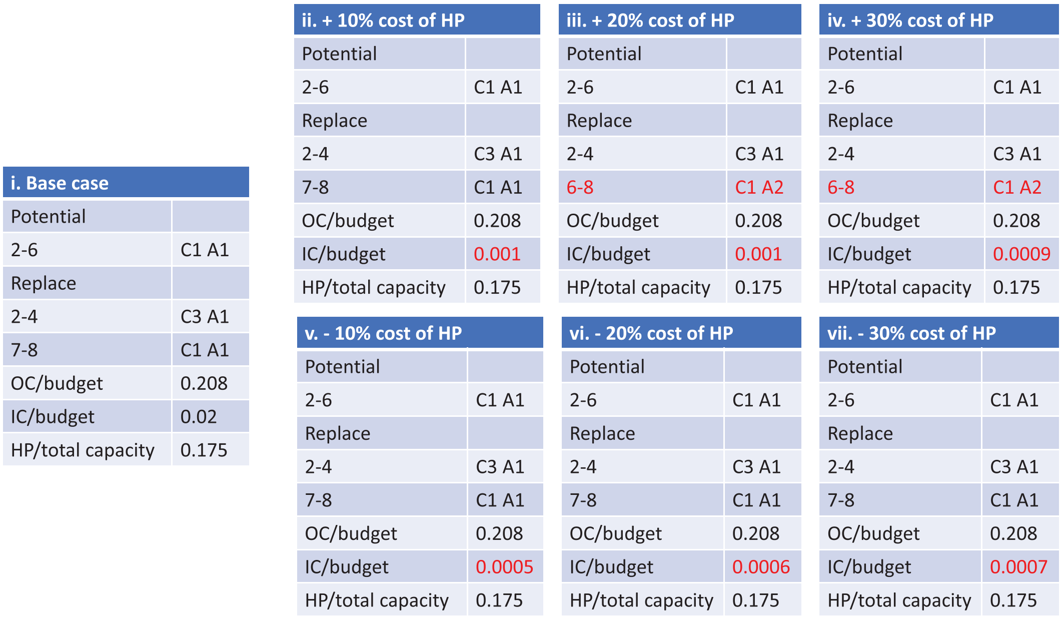


FIGURE 4 Trend of investment (ic) and operational (oc) costs with descending order of COP of heat pump. With non-dispatchable generation units (ic1, oc1), without non-dispatchable generation units (ic2, oc2)



i. Base case	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.208
IC/budget	0.02
HP/total capacity	0.175

ii. + 10% cost of HP	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.208
IC/budget	0.001
HP/total capacity	0.175

iii. + 20% cost of HP	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.208
IC/budget	0.001
HP/total capacity	0.175

iv. + 30% cost of HP	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.208
IC/budget	0.0009
HP/total capacity	0.175

v. - 10% cost of HP	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.208
IC/budget	0.0005
HP/total capacity	0.175

vi. - 20% cost of HP	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.208
IC/budget	0.0006
HP/total capacity	0.175

vii. - 30% cost of HP	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.208
IC/budget	0.0007
HP/total capacity	0.175

FIGURE 5 Analyzing the ratio between the cost of heat pump and COP. Network interventions without non-dispatchable generation unit with heat pump COP 1.5

Technological innovations often fail to be cost-effective. This in turn creates a lag in the wider adoption of technologies.

Figure 5 illustrates how the ratio between the cost of a heat pump and COP influences the network interventions. The reconfiguration decisions are prominent when the cost of a heat pump starts to increase in comparison to the base case (1:1). While the total capacity of non-dispatchable generators and heat pumps installed over the time horizon remains the same, it was observed that the rate at which capacity is built throughout the 10-year horizon varies significantly. At the point when the cost of heat pumps starts to increase it is more cost-effective to perform network reconfiguration in place of building additional heat pump units to meet the demand. While this trend continues, more restructuring decisions are observed in place of additional capacity installations.

Additional sensitivity analyses have been conducted in which the COP value is kept constant at 2.5 while the cost of a heat pump gradually decreases. Particularly when non-dispatchable generation units are an option, the decrease in the cost of heat pumps does not alter the network intervention decisions as presented before. Indeed there are changes in investment and operational costs, which are trivial, as changes in the unitary cost would be reflected in overall costs. This is the reason why the results for this particular test are not presented in this paper.

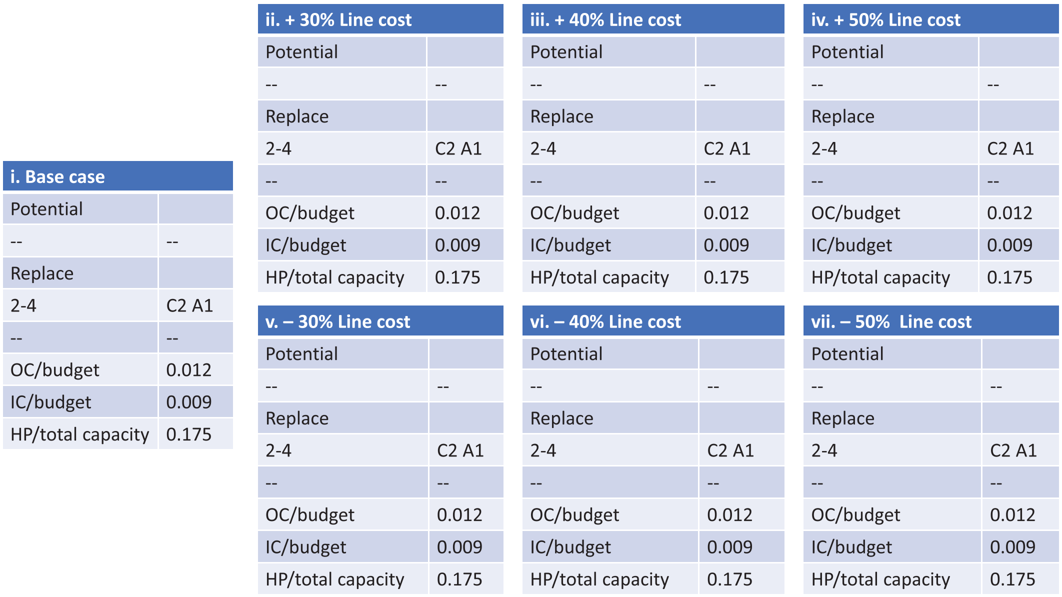
3.2.2 | HP cost vs new line cost

Figure 6 shows how the decisions change when the cost of new lines (C1 and C2) changes in comparison with the cost of a heat pump. The line types vary based on cost and capacity, in particular C1 costs more than C2. After fixing the cost of a heat pump, a sensitivity analysis is conducted by increasing and decreasing the cost of the lines. Note that the COP is set to 2 for this particular case study.

As shown in Figure 6 the change in the cable costs affect the investment and operational costs accordingly. While there are no network interventions, one can note that the investment and operational costs match the proportional change in the cable costs. However, it was also observed that there is a change in the pattern of the installation of heat pump capacities over the time horizon in each case. Expanding on that, when the cost increases/decreases, then the model chooses to wait/build capacities accordingly.

3.2.3 | COP vs heat demand

Figure 7 displays how the decisions change when the heat energy consumption changes. When the demand is increased at the rate of 10%, new potential line capacities are built to meet the additional demand. The total value of the heat pump capacity installed for each case is



i. Base case	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

ii. + 30% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

iii. + 40% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

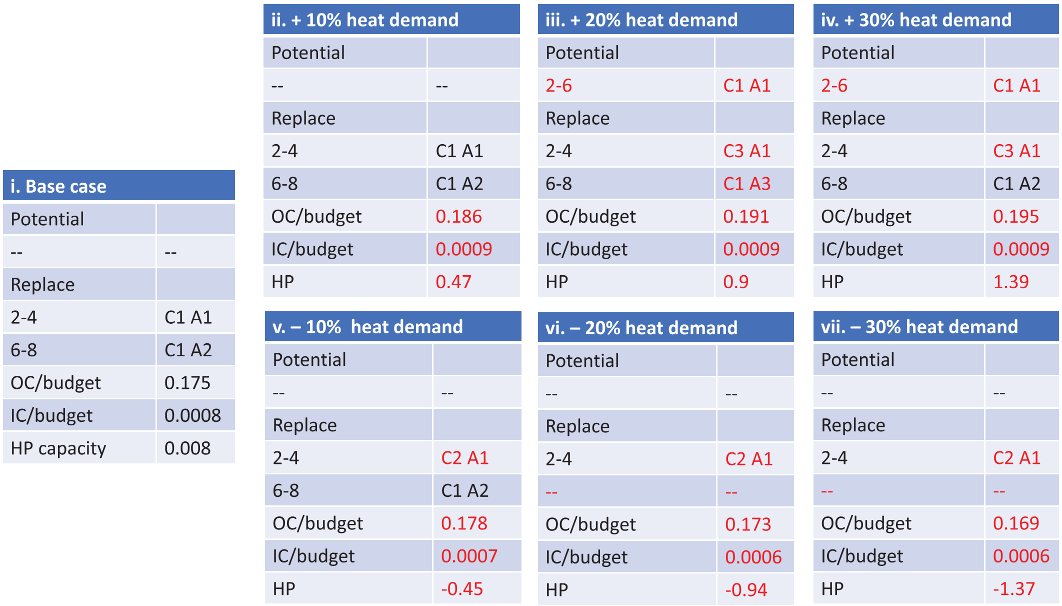
iv. + 50% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

v. – 30% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

vi. – 40% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

vii. – 50% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

FIGURE 6 Network interventions comparing cost of heat pump and line



i. Base case	
Potential	
--	--
Replace	
2-4	C1 A1
6-8	C1 A2
OC/budget	0.175
IC/budget	0.0008
HP capacity	0.008

ii. + 10% heat demand	
Potential	
--	--
Replace	
2-4	C1 A1
6-8	C1 A2
OC/budget	0.186
IC/budget	0.0009
HP	0.47

iii. + 20% heat demand	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A3
OC/budget	0.191
IC/budget	0.0009
HP	0.9

iv. + 30% heat demand	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.195
IC/budget	0.0009
HP	1.39

v. – 10% heat demand	
Potential	
--	--
Replace	
2-4	C2 A1
6-8	C1 A2
OC/budget	0.178
IC/budget	0.0007
HP	-0.45

vi. – 20% heat demand	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.173
IC/budget	0.0006
HP	-0.94

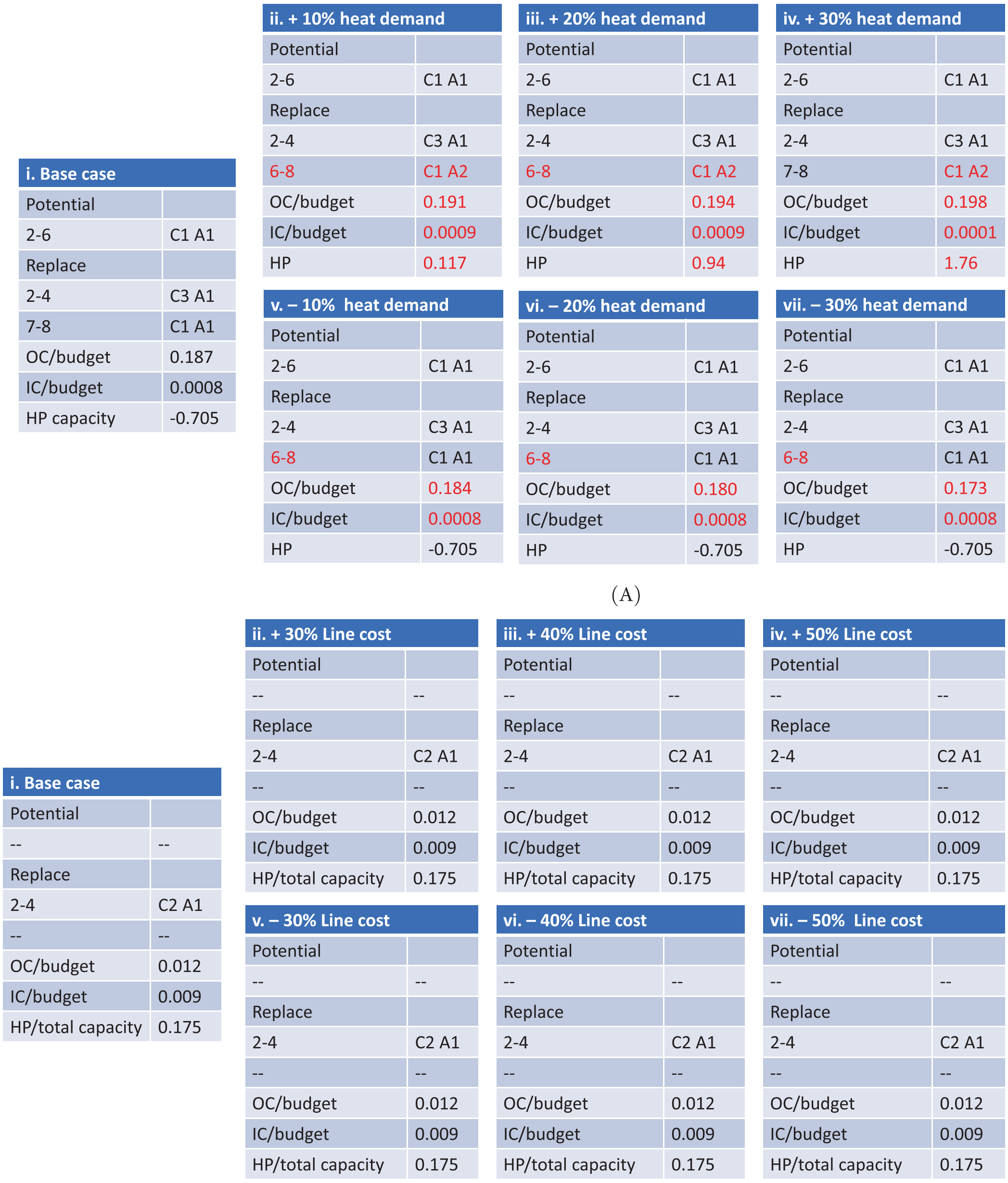
vii. – 30% heat demand	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.169
IC/budget	0.0006
HP	-1.37

FIGURE 7 Decisions when comparing COP and change in heat consumption

normalized using the formula *value* = (data−mean of data)/SD of the data.

Alongside network restructuring, other events take place in order to maintain the power flow. While heat demand decreases, network restructuring takes place and no new lines capacities are built. As opposed to previous cases, when the heat demand changes, the total capacity built over the planning horizon changes. Similar to previous cases, changes in the patterns of heat pump capacity building over the years continue. It is evident that a part of the demand is met by the newly built heat pump units and new line capacities that manage the power flow. When the heat demand increases by 20%, significant network interventions like installing potential lines along with network restructuring are observed. The trend of proportional rising heat pump capacity with rising demand can be clearly observed from the experiment.

Network interventions are also matched with new heat pump installations to generate the additional power that is required to meet demand. Operational and



i. Base case	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP capacity	-0.705

ii. + 10% heat demand	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.191
IC/budget	0.0009
HP	0.117

iii. + 20% heat demand	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.194
IC/budget	0.0009
HP	0.94

iv. + 30% heat demand	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A2
OC/budget	0.198
IC/budget	0.0001
HP	1.76

v. – 10% heat demand	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.184
IC/budget	0.0008
HP	-0.705

vi. – 20% heat demand	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.180
IC/budget	0.0008
HP	-0.705

vii. – 30% heat demand	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.173
IC/budget	0.0008
HP	-0.705

(A)

i. Base case	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

ii. + 30% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

iii. + 40% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

iv. + 50% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

v. – 30% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

vi. – 40% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

vii. – 50% Line cost	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.012
IC/budget	0.009
HP/total capacity	0.175

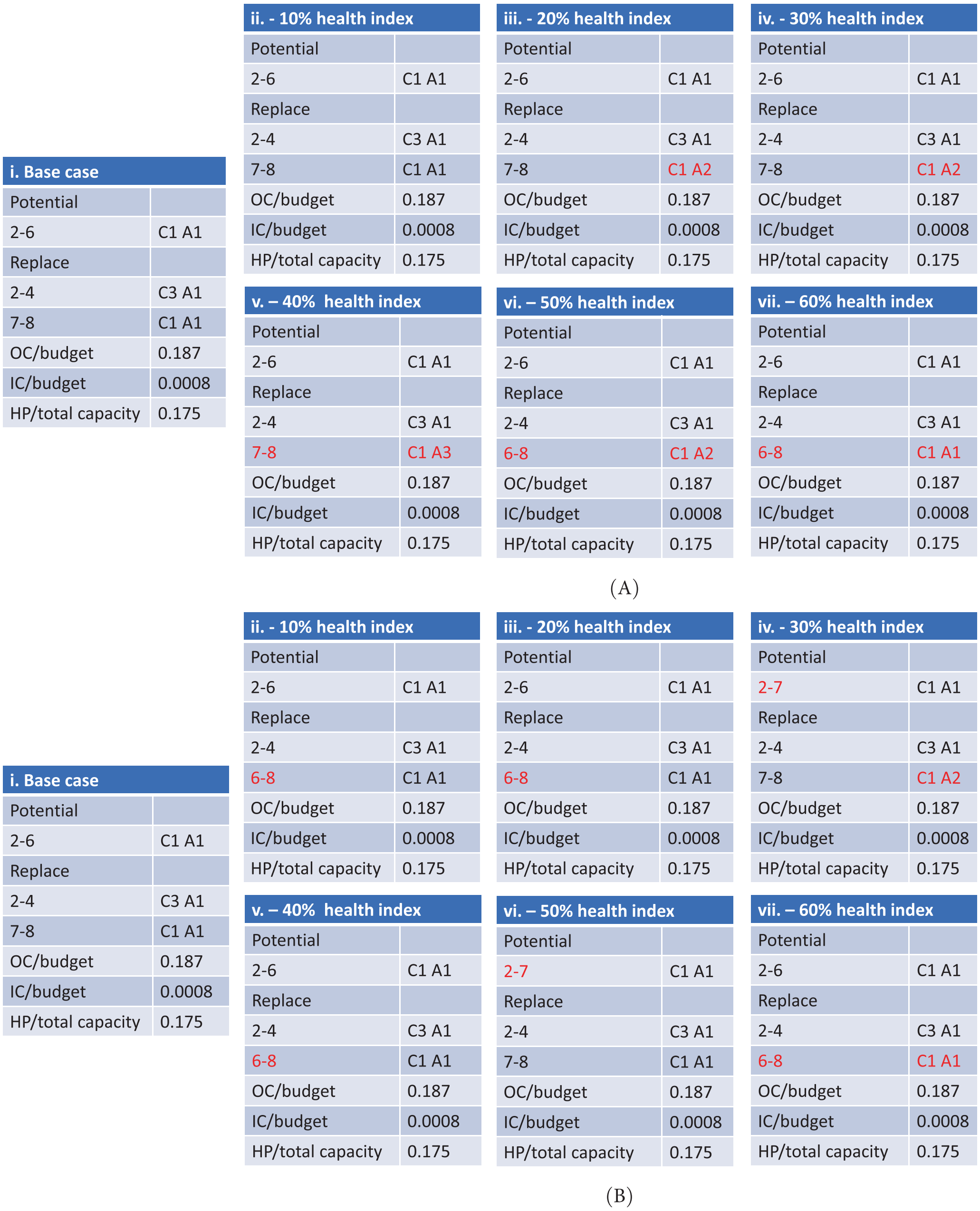
(B)

FIGURE 8 Network interventions and decisions under various (network condition) scenarios of tower 2, 4, and 8. (A) Decisions when heat energy consumption is linearly rising at node 8 and health of tower 2 is half. (B) Decisions when tower 2 condition varies

investment costs are also increasing over the time horizon. Indeed, installing additional heat pumps is an optimal decision for meeting the change in heating demand in comparison to additional costly, extensive network interventions.

3.2.4 | Implication of condition of the tower

A health index (HI) is utilized to indicate the condition of the transmission tower.[31] Lower HI indicates a lower operational capacity, and in the proposed model, this translates to a lower transmission capacity. The representative value of HI ranges from 0 to 1, and the lower the value the lower the associated capacity of transmission lines. A typical transmission tower facilitates multiple overhead lines. Depending on the number of lines a tower facilitates, the associated risk changes. A tower acting as a junction to facilitate three connections, for instance, is a high-risk tower, whereas a tower with one connection is low-risk because it is serving one consumer. Consumer types (industrial, residential,



i. Base case	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

ii. - 10% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iii. - 20% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iv. - 30% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

v. – 40% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A3
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vi. – 50% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vii. – 60% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

(A)

i. Base case	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

ii. - 10% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iii. - 20% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iv. - 30% health index	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

v. – 40% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vi. – 50% health index	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vii. – 60% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

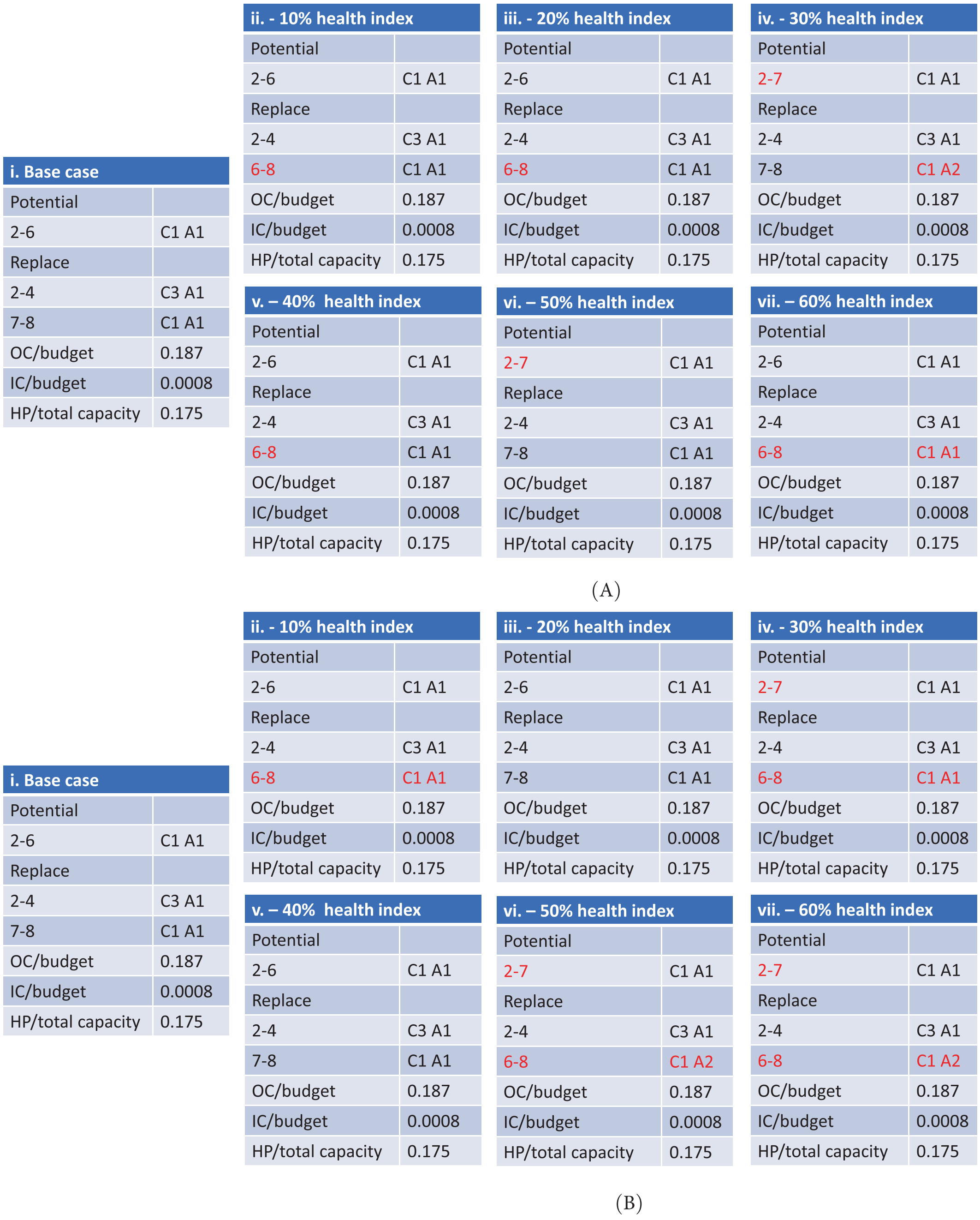
(B)

FIGURE 9 Sensitivity of tower 8, (2, 8) health indices. (A) Decisions as the health index of tower 8 varies. (B) Decisions with change in the tower 2 & 8 health index

commercial, office building, emergency care, etc.) might also be used in the risk classification function. In this work, the number of connections is used as a risk metric.

In Figures 8, 9, and 10 the decisions and network interventions under various health indices are presented. Figure 8A presents the scenario when the heat energy consumption is rising, and when the HI of tower 2 is half, compared to the cases presented in previous sections. Figure 8B depicts the decisions when the condition of tower 2 is changing. The sensitivity case with a change in the condition of tower 8, which is at the end of the network, is presented in Figure 9A. Let us now move to the scenario where two towers are deteriorating simultaneously. The decisions under these conditions are detailed in Figure 9B. Decisions regarding the degradation of tower 4 are displayed in Figure 10A. Finally, a critical network condition is investigated wherein towers 2, 4, and 8 are deteriorating simultaneously. The results from this condition are presented in Figure 10B.

It is observed that as poles' health deteriorates, there are changes in the pattern of network interventions. However, minor changes in the network restructuring are observed when the health indices of poles are considered. It was observed that such changes were becoming



i. Base case	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

ii. - 10% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iii. - 20% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iv. - 30% health index	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

v. – 40% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vi. – 50% health index	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vii. – 60% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

(A)

i. Base case	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

ii. - 10% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iii. - 20% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iv. - 30% health index	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

v. – 40% health index	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vi. – 50% health index	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vii. – 60% health index	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

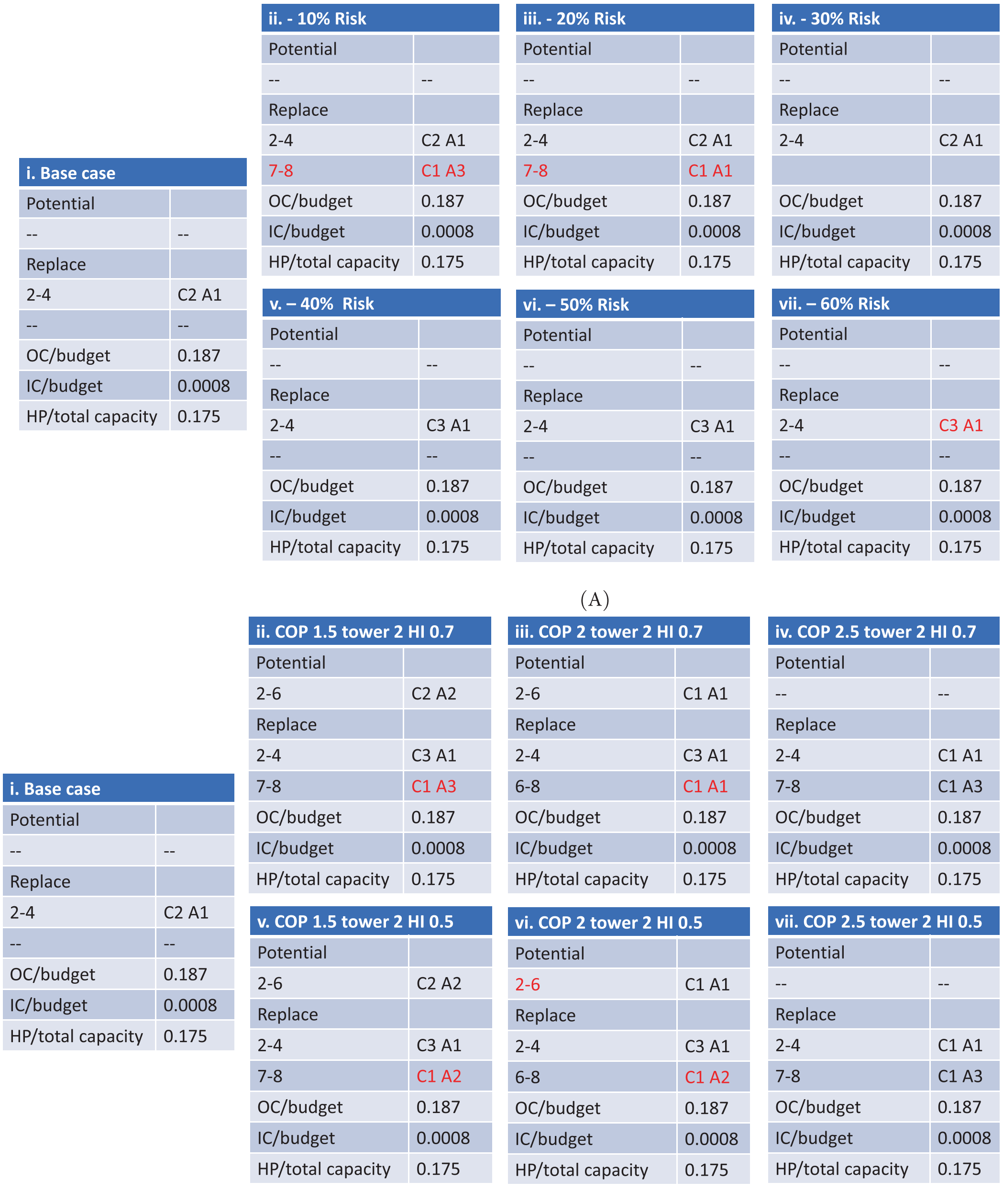
(B)

FIGURE 10 Sensitivity of transmission tower condition. (A) Decisions with change in the tower 4 health changing. (B) Decisions with change in the tower 2, 4, & 8 health changing

more substantial as the construction time increased. It can also be observed that the sole deterioration of a tower's health is not a sufficient condition for network restructuring and reconfiguration.

The construction of new lines, or modifications of existing ones, could take 6 months to several years to complete. According to the report from Berkeley lab on building electric transmission lines,[63] there is a range of factors that contribute to risk in capacity building projects. Some of these factors are acquiring required permissions, funding acquisition, potential demand growth, and risks associated with civil construction works. In this work, a cumulative risk factor is used to represent a range of risks as listed before.

Figure 11A presents the decisions when the risk associated with towers 2, 4, and 8 varies. Note that the risk factor is 1 when the demand must be met at all points in time, while the reduced flexibility through the scope for load shedding increases. When the network operator deems the aforementioned towers to have less risk the



i. Base case	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

ii. - 10% Risk	
Potential	
--	--
Replace	
2-4	C2 A1
7-8	C1 A3
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iii. - 20% Risk	
Potential	
--	--
Replace	
2-4	C2 A1
7-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iv. - 30% Risk	
Potential	
--	--
Replace	
2-4	C2 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

v. – 40% Risk	
Potential	
--	--
Replace	
2-4	C3 A1
--	--
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vi. – 50% Risk	
Potential	
--	--
Replace	
2-4	C3 A1
--	--
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vii. – 60% Risk	
Potential	
--	--
Replace	
2-4	C3 A1
--	--
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

(A)

i. Base case	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

ii. COP 1.5 tower 2 HI 0.7	
Potential	
2-6	C2 A2
Replace	
2-4	C3 A1
7-8	C1 A3
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iii. COP 2 tower 2 HI 0.7	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

iv. COP 2.5 tower 2 HI 0.7	
Potential	
--	--
Replace	
2-4	C1 A1
7-8	C1 A3
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

v. COP 1.5 tower 2 HI 0.5	
Potential	
2-6	C2 A2
Replace	
2-4	C3 A1
7-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

vi. COP 2 tower 2 HI 0.5	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A2
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

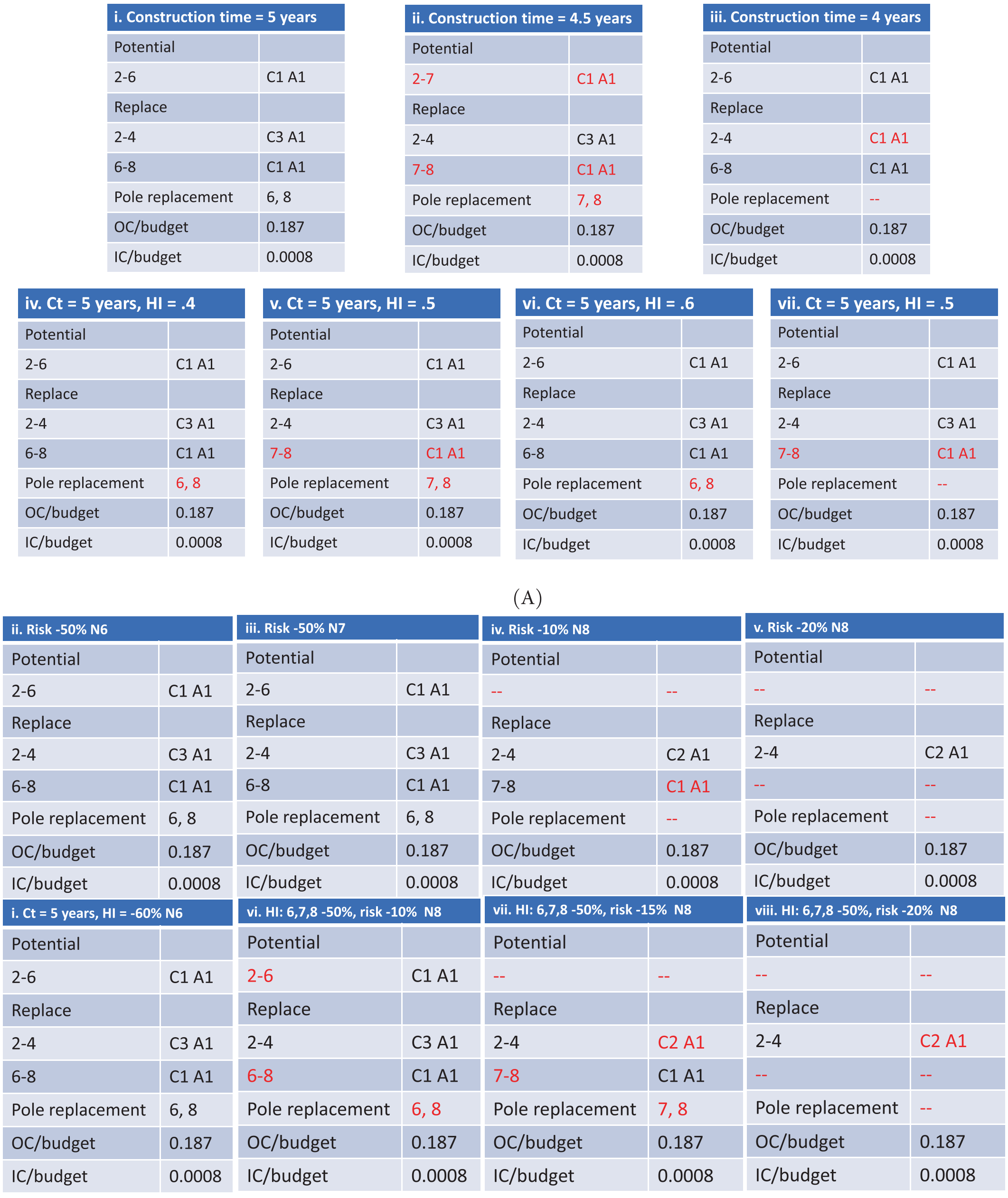
vii. COP 2.5 tower 2 HI 0.5	
Potential	
--	--
Replace	
2-4	C1 A1
7-8	C1 A3
OC/budget	0.187
IC/budget	0.0008
HP/total capacity	0.175

(B)

FIGURE 11 Decisions when tower health and COP are considered. (A) Sensitivity of health indices of towers 2, 4, 8. (B) Sensitivity of health indices of tower 2 and COP

network restructuring decisions change. Namely, with 10% reduction in risk there is a new restructuring decision (line 7-8 with cable type 1 on year 3) in comparison to the base case (without any risk). It can be observed that as the risk decreases, the number of network interventions significantly decreases. When the risk factor decreases from 30% to 40% for instance, the optimal decision is to dismantle the existing line 2-4 in year 1. This indicates that the risk factor enables the network operator to make optimal decisions apt to the existing circumstances.

Figure 11B presents two sets of scenarios where the health index of a tower and the COP of a heat pump varies. This scenario sheds light on how the level of a tower's health could affect the network expansion. For example, when the COP is high (2.5) but the health is low (0.7), there are neither network reconfiguration nor potential lines. When the COP is lower (2) the optimal decision is to invest in new lines and perform restructuring. This illustrates that network condition is an important factor in determining the minimum efficiency level of a heat pump to justify installation. This is particularly important



(A)

i. Construction time = 5 years	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0008

ii. Construction time = 4.5 years	
Potential	
2-7	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
Pole replacement	7, 8
OC/budget	0.187
IC/budget	0.0008

iii. Construction time = 4 years	
Potential	
2-6	C1 A1
Replace	
2-4	C1 A1
6-8	C1 A1
Pole replacement	--
OC/budget	0.187
IC/budget	0.0008

iv. Ct = 5 years, HI = .4	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0008

v. Ct = 5 years, HI = .5	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
Pole replacement	7, 8
OC/budget	0.187
IC/budget	0.0008

vi. Ct = 5 years, HI = .6	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0008

vii. Ct = 5 years, HI = .5	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
7-8	C1 A1
Pole replacement	--
OC/budget	0.187
IC/budget	0.0008

(B)

ii. Risk -50% N6	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0008

iii. Risk -50% N7	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0008

iv. Risk -10% N8	
Potential	
--	--
Replace	
2-4	C2 A1
7-8	C1 A1
Pole replacement	--
OC/budget	0.187
IC/budget	0.0008

v. Risk -20% N8	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
Pole replacement	--
OC/budget	0.187
IC/budget	0.0008

i. Ct = 5 years, HI = -60% N6	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0008

vi. HI: 6,7,8 -50%, risk -10% N8	
Potential	
2-6	C1 A1
Replace	
2-4	C3 A1
6-8	C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0008

vii. HI: 6,7,8 -50%, risk -15% N8	
Potential	
--	--
Replace	
2-4	C2 A1
7-8	C1 A1
Pole replacement	7, 8
OC/budget	0.187
IC/budget	0.0008

viii. HI: 6,7,8 -50%, risk -20% N8	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
Pole replacement	--
OC/budget	0.187
IC/budget	0.0008

FIGURE 12 Decisions when the construction time, tower health, and associated risk are considered. (A) Sensitivity of construction time and tower health indices of tower 2, 4, 8. (B) Decisions when risk is factored in

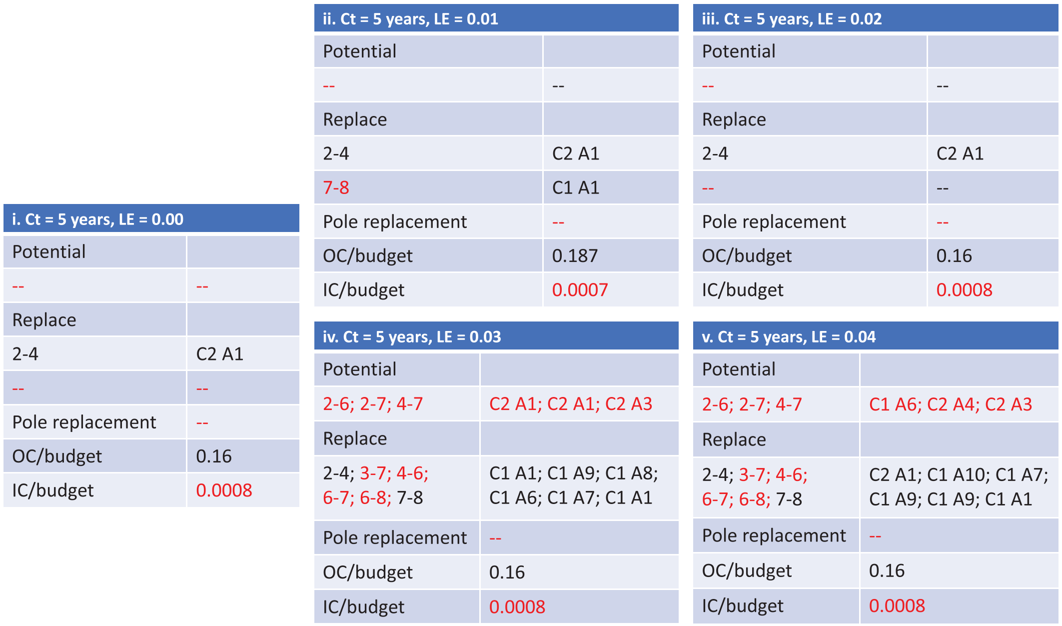
in setting up the minimum parameters for the assets to be listed in a VPP.

When the construction time was varied from 5 to 4 the decision, in terms of network interventions and capacity building, changed as presented in Figure 12A. When the construction time is 5 years the optimal decision is to replace poles (6 and 8), build new line capacity (2-6 using line C1 on year 1), replace the existing line (6-8 using line C1 on year 1) and restructure the network by dismantling line 2-4. Pole replacement is essentially a trade-off between construction time and the cost of replacement. In this case, if the construction time is longer than 4.5 years the optimal decision is to replace the towers with fewer network interventions. When construction time is reduced, the number and type of network interventions reduce significantly. Factoring the condition of the tower into the decision-making process changes the overall network structure. In particular, when the construction time is 5 years and the condition of a tower is 60% of its original capacity, an optimal decision is to refrain from tower replacement. Similar to an urban power network, the risks at the edge of a network (path 6-7-8) are now included in the decision making process. The results presented in Figure 12B illustrate how risk impacts optimal network expansion decisions. When the risk in node 8 is 10% there are fewer network interventions as compared to 50% risk seen in node 7. Fixing the health of node 8 at 60%, when the risk is 100%, the optimal decision is to replace towers 6 and 8. When the risk is reduced by 10% the tower replacements are not required. This implies that the health of tower 8 is both critical and urgent given the risk. However, the health of tower 7 might be critical, but the associated risk is low, therefore not urgent.

Note that a particular node might have a lower health index, indicating a lower operational capacity, while still having a lower risk. This translates to a scenario of important, but not critical, conditions. In this case, load shedding is permitted to the same extent as the risk factor. In another scenario, wherein the risk is high and the health index is low, all the demand must be met. Often such scenarios appear at sub-urban/rural areas at the edge of a network with weak demand potential. Alternatively, they might also appear in an old line corridor in an urban area, or at a line connecting to an industrial consumer.

"Learning effect" is the influence of experience gained over time from repeated activities. In mathematical optimization this is realized by discounting the cost in the objective function. The authors have thoroughly studied and illustrated the effect of technological learning in a previous work in Reference 23. In this paper, a sensitivity analysis is conducted to understand the impact of the learning effect on the model's decisions when the network condition is factored into the model parameters. The learning effect is gradually increased by 10% and the results are detailed in the tables in Figure 13. It can be observed from the results that the number of network interventions significantly increases as the learning effect increases. The reasoning behind the decisions is the effect of discounted cost. In particular, when the learning effect has increased by 30% a significant number of network interventions, including reconfiguration decisions, are observed. This is a pivotal point as with further increments, from 30% to 40%, the changes in the decisions are trivial.

Typically, as the length of a line to be constructed increases, the associated costs follow the same trend. In expansion planning models, the actual length of lines is often aggregated to simplify the computational burden. Next, the impact of the length of existing lines on expansion decisions is investigated. The length of existing lines is increased by 10%, and the decisions are compared to a base case (with aggregated line lengths). The results are presented in the tables in Figure 14. There is a significant change in terms of cost and network interventions when the line lengths are considered. As line length starts to increase, the number of interventions follows, and the main choice is a shift towards a cheaper cable type. Since the cheaper cable also has a lower performance (ie, lower capacity), the model has to include more interventions to get a mix that can allow for power



i. Ct = 5 years, LE = 0.00	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
Pole replacement	--
OC/budget	0.16
IC/budget	0.0008

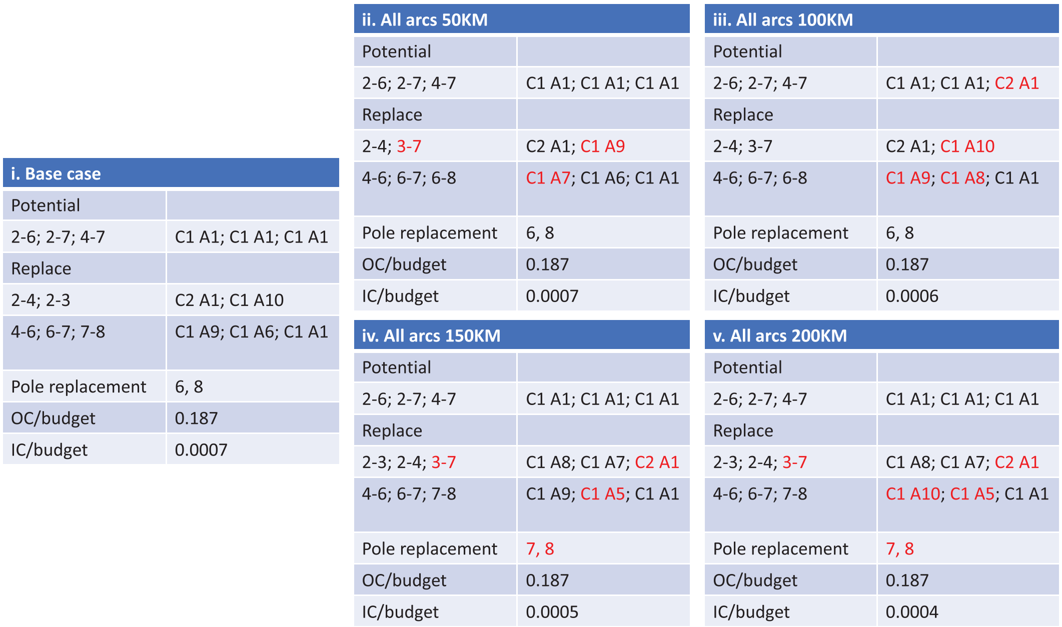
ii. Ct = 5 years, LE = 0.01	
Potential	
--	--
Replace	
2-4	C2 A1
7-8	C1 A1
Pole replacement	--
OC/budget	0.187
IC/budget	0.0007

iii. Ct = 5 years, LE = 0.02	
Potential	
--	--
Replace	
2-4	C2 A1
--	--
Pole replacement	--
OC/budget	0.16
IC/budget	0.0008

iv. Ct = 5 years, LE = 0.03	
Potential	
2-6; 2-7; 4-7	C2 A1; C2 A1; C2 A3
Replace	
2-4; 3-7; 4-6; 6-7; 6-8; 7-8	C1 A1; C1 A9; C1 A8; C1 A6; C1 A7; C1 A1
Pole replacement	--
OC/budget	0.16
IC/budget	0.0008

v. Ct = 5 years, LE = 0.04	
Potential	
2-6; 2-7; 4-7	C1 A6; C2 A4; C2 A3
Replace	
2-4; 3-7; 4-6; 6-7; 6-8; 7-8	C2 A1; C1 A10; C1 A7; C1 A9; C1 A9; C1 A1
Pole replacement	--
OC/budget	0.16
IC/budget	0.0008

FIGURE 13 Variation in decisions with introduction of learning effect (LE)



i. Base case	
Potential	
2-6; 2-7; 4-7	C1 A1; C1 A1; C1 A1
Replace	
2-4; 2-3	C2 A1; C1 A10
4-6; 6-7; 7-8	C1 A9; C1 A6; C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0007

ii. All arcs 50KM	
Potential	
2-6; 2-7; 4-7	C1 A1; C1 A1; C1 A1
Replace	
2-4; 3-7	C2 A1; C1 A9
4-6; 6-7; 6-8	C1 A7; C1 A6; C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0007

iii. All arcs 100KM	
Potential	
2-6; 2-7; 4-7	C1 A1; C1 A1; C2 A1
Replace	
2-4; 3-7	C2 A1; C1 A10
4-6; 6-7; 6-8	C1 A9; C1 A8; C1 A1
Pole replacement	6, 8
OC/budget	0.187
IC/budget	0.0006

iv. All arcs 150KM	
Potential	
2-6; 2-7; 4-7	C1 A1; C1 A1; C1 A1
Replace	
2-3; 2-4; 3-7	C1 A8; C1 A7; C2 A1
4-6; 6-7; 7-8	C1 A9; C1 A5; C1 A1
Pole replacement	7, 8
OC/budget	0.187
IC/budget	0.0005

v. All arcs 200KM	
Potential	
2-6; 2-7; 4-7	C1 A1; C1 A1; C1 A1
Replace	
2-3; 2-4; 3-7	C1 A8; C1 A7; C2 A1
4-6; 6-7; 7-8	C1 A10; C1 A5; C1 A1
Pole replacement	7, 8
OC/budget	0.187
IC/budget	0.0004

FIGURE 14 Decisions when the line lengths are taken into account

flow and overcome the lower performance of cheaper cables. To illustrate Table v of Figure 14 has six replacements as part of network restructuring compared to Table i of Figure 14. The location of demand and generation units and line capacities are among the key factors for this decision change. Thereby in an expansion decision-making process the network condition plays a substantial role (Figure 14).

4 | CONCLUSIONS AND FUTURE SCOPE

This paper investigates the impact of resilient power network planning while considering how the condition of the network impacts investment and operational costs for a virtual power plant in an integrated energy system. A virtual power plant provides a platform for facilitating local energy transactions with an integrated energy system. The proposed model takes into account both heating and electric demands. The choice is whether installing local heat pumps to meet the heating energy consumption needs is among the optimal decisions for capacity building. Reconfiguration, restructuring, and tower replacement decisions are part of the network intervention options. The condition of the network is represented in the form of a health index of the towers, risk factors associated with the location of a tower, and maintenance costs of lines. A long-term planning horizon of 10 years is included, following the typical decision process for network reinforcement in the industry. A multi-horizon decision-making process is adopted where a decision can be taken within the set time horizon based on the current status and future projections. In addition, the effect of learning from experience is factored into the decision-making, and this is represented in the form of the learning effect. A wide range of experiments with extensive sensitivity is conducted to identify and characterize the trade-offs between the network condition and capacity building in terms of cost-benefit.

Experimental results validate that when the network conditions are factored in, the model decisions vary significantly in comparison to that of a representation without network conditions. Particularly, there is a multi-fold impact on operational costs and network interventions. The inclusion of replacement decisions for towers and lines reflects the practical reality of network operations. Furthermore, a tower's importance, determined through a risk factor, demonstrates how consumer-type could influence decisions. The simulations clearly demonstrate that it is cost-optimal to overlook the condition of a tower if it is serving a relatively low volume of growth. In other words, if the risk of a tower is low, and the health of a tower is also low, an optimal decision could be to overlook this reinforcement through investment in a new tower. This analysis provides clarity for the system operator, who must decide which tower to replace or maintain while avoiding costly investments.

From the results of the computational experiments, it was observed that at COP 3 and beyond, heat pumps become an optimal option for investment, compared to network interventions. Construction time impacts the network restructuring decisions. When the construction time is shorter than 4.5 years, the number of network interventions is higher than when construction time is beyond 4.5 years. It was also observed that a particular tower can be both urgent and critical, meaning that a small change in the condition of the tower would have an immediate economic impact. Note that these quantifications are valid within the specific context of the multi-horizon reliability-oriented network restructuring problem.

In summary, this analysis, which includes network conditions in the decision process for network expansion planning, demonstrates how network conditions can drastically impact decisions in terms of both network interventions and investments in a long time horizon. The risk factor in an area (node) has a higher weight than the condition of lines or nodes in an expansion decision. For instance, an area with a deteriorated condition does not warrant an investment if the associated risk is low. The allocation of risk factors is an effective way for the network owner to prioritize the network reinforcements which, in turn, leads to a reduction in investments. A heat pump is an effective technology to avoid or postpone network investment decisions if the coefficient of performance of the heat pump is greater than or equal to 2.5. A virtual power plant can enable an efficient and effective power network by bridging together behind the meter and front-of-meter energy infrastructure. Network interventions are influenced by construction time. In the analysis, the construction time of 4.5 years or more has a significant impact on investments and network interventions. Typically the construction of overhead transmission lines ranges from 5 to 10 years. Thereby it is important to consider the condition and risk factors in a network where construction time is more than 4.5 years.

Future research directions include particularly radial and meshed power network structures under various geographical conditions. Another dimension is to investigate more accurate calibration of the health indexes through the inclusion of features associated with types of faults and automation potential. The future decentralized and distributed power network relies on a resilient power network enabled by digitization. A follow-up research work shall introduce line loading factors, as well as dynamic and mobile loads, such as electric vehicles.

NOMENCLATURE

Indexes

t	time step
a	years
i, j	nodes of the grid

Parameters

$D_{i,t,a}$	power demand
$D_{i,t,a}^{heat}$	heat demand
r	iNTEREST rate
$E_{i,j}$	binary parameters equal to 1 if a line exists between node *i j*
$\overline{E}_{i,j}$	capacity of the cable
Z	construction time
$BigM$	a very big number
$N_{i,j}^{pot}$	parameter that is equal to 1 if a potential arc can be placed between node *i* and *j*
$\overline{N}_c$	capacity of the new cable of type c
$X_{i,j}$	BInary parameter equal to 1 if the users wants to evaluate replacement of an existing cable, 0 otherwise
V_i^{health}	state of health of a tower in a nosw
V^{CRF}	capital recovery factor for the installation of a new tower
V^{life}	estimated life of a new tower
V^{cost}	estimated cost of a new tower
$V_{i,a}^{risk}$	risk factor associated to a node
H^{CRF}	capital recovery factor for the installation of a new heat pump
H^{life}	estimated life of a new heat pump
H^{cost}	estimated cost of a new heat pump
COP	coefficient of performance of a heat pump

Variables

$f_{i,t,a}^{in}$	total power flow into a node
$p_{i,j,t,a}$	power flow in each arc
$k_{i,j,c,a}$	binary variable equal to 1 if an existing arc i,j is replaced by a potential cable of type c, 0 otherwise
γ_i	binary variable equal to 1 if an existing pole is replaced with a new one, 0 otherwise
$y_{i,j,c,a}$	binary variable equal to 1 if a potential arc is created between nodes *i* and *j*, 0 otherwise
$d_{i,t,a}^{heat01}$	portion of heat demand to be met through existing traditional heating systems
$d_{i,t,a}^{heat02}$	portion of heat demand to be met through new heat pump installation
$h_{i,a}$	new aggregated heat pump capacity installed on a node i in a certain year a

ACKNOWLEDGEMENT

This work is supported by the Eesti Teadusagentuur grant PUTJD915.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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How to cite this article: Mishra S, Bordin C, Wu Q, Manninen H. Resilient expansion planning of virtual power plant with an integrated energy system considering reliability criteria of lines and towers. *Int J Energy Res*. 2022;1-26. doi:10.1002/er.8093