

# From Sun and Wind to Thermal Comfort: A Techno-Economic Optimization Framework for Renewable Electrification of Heating and Cooling in Iran

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## Abstract

This study develops an optimization-based planning model for the deployment of renewable energy resources to meet electrified space heating and cooling demands. The model integrates building heat transfer characteristics, renewable energy potentials, and electricity transmission network constraints. Its objective is to minimize total investment and operational costs of generation, storage, and transmission, while capturing seasonal variability in supply and demand. The framework also evaluates the effects of finer temporal resolution and multiple operational periods through scenario-based simulations. Heating and cooling demands are estimated using degree-day metrics combined with building thermal transfer equations, assuming full electrification by renewable sources. Two strategies for heating electrification are investigated: assigning a predetermined share to each province, and optimizing the spatial distribution of electrification across provinces to meet overall targets. The model is applied to real-world data from Iran, which features diverse climates and substantial solar and wind potential. Results suggest widespread deployment of solar PV across most provinces, while wind development is concentrated in eastern regions such as Khorasan. Sensitivity analysis on storage system costs shows a balanced solar-wind combination when the storage prices is in the range \$100-150/kWh. For the prices below or above this range respectively the solar or wind power plants dominate the generation mix. Transmission network expansion is most beneficial in provinces that serve as renewable hubs or major demand centers, though local supply is generally prioritized. Overall, findings indicate that the priority of heating electrification projects varies significantly among provinces, highlighting the importance of spatially differentiated planning strategies.

**Keywords:** Heating and Cooling Electrification, Solar and Wind Integration, Energy Systems in Iran, Degree Day Method.

## Nomenclature

### *Indices and sets*

$p$	Index of regions
$k$	Index of renewable power generation technologies
$s$	Index of seasons ( $s^{summer}, s^{winter}$ )
$t$	Index of day and night time periods ( $t^{day}, t^{night}$ )
$m$	Index of power transmission technologies
$j$	Index of energy storage technologies
$h$	Index of hours
$d$	Index of days
$\mathcal{T}^{peak}$	Set of peak period hours

### Parameters

$e_{k,p,h}$	Energy generated by renewable power plant type $k$ located in region $p$ at hour $h$
$\rho^{loss}$	Average network loss coefficient per unit length of the power transmission network
$D_p$	Average distance between region $p$ and other regions in the country
$CF_{p,k,s,t}$	Capacity factor of renewable power plants of type $k$ in region $p$ at time $t$ in season $s$
$X_{p,m}^0$	Existing transmission capacity of type $m$ between region $p$ and other regions
$\Delta_{p,s,t}$	Duration of nighttime or daytime in season $s$ at time $t$ in region $p$
$\Delta^s \setminus \Delta^w$	Duration of summer/winter period
$L_{p,s,t}^{cooling} / L_{p,s,t}^{heating}$	Electricity demand for cooling/heating systems in region $p$ in season $s$ at time $t$
$\alpha_p^e$	Electrification factor of region $p$ , that is the fraction of heating demand supplied electrically.
$\eta_{p,j,s,t}^{dch}$	Discharge efficiency of storage system type $j$ in region $p$ in season $s$ at time $t$
$\eta_{p,j,s,t}^{ch}$	Charge efficiency of storage system type $j$ in region $p$ in season $s$ at time $t$
$dist_{p,p'}$	Distance between regions $p$ and $p'$
$N$	Number of regions
$OC_k$	Operating cost of power plant with technology $k$
$r$	Discount rate
$n_k$	Useful lifetime of technology $k$
$IC_k^{Gen}$	Investment cost for generation technology type $k$
$IC_m^{Tr}$	Investment cost for power transmission technology type $m$
$IC_j^{stg}$	Investment cost for electricity storage technology type $j$
$a_i$	Area of different building envelope sections
$u_i$	Heat transfer coefficient of different building envelope sections
$HDD$	Heating degree days
$CDD$	Cooling degree days
$HL/CL$	Heating\Cooling energy demand.
$P^h / P^c$	Heating\Cooling power demand.
$T_d$	Average temperature during hours of day $d$
$Th^{cooling}$	Cooling threshold temperature
$Th^{heating}$	Heating threshold temperature
$A$	Building area
$U$	Overall heat transfer coefficient (U-value)
$\eta_p^h / \eta_p^c$	Energy efficiency coefficient of heating/cooling systems in region $p$
$COP_p^c$	Coefficient of performance (COP) of cooling systems in region $p$

### Variables

$Z$	Objective function
$Z^{Gen}(\cdot)$	Investment cost function for power generation expansion
$Z^{stg}(\cdot)$	Investment cost function for energy storage expansion
$Z^{Tr}(\cdot)$	Investment cost function for power transmission network expansion

$Z^{Operation}(\cdot)$	System operation cost function
$X_{k,p}^G$	Installed capacity of renewable generation technology $k$ in region $p$
$X_{p,j}^{stg}$	Installed capacity of storage technology $j$ in region $p$
$X_{p,m}^l$	Installed capacity of power transmission technology $m$ in region $p$
$P_{p,k,s,t}$	Power output of renewable power plant with technology $k$ in season $s$ at time $t$ in region $p$
$F_{p,s,t}$	Total power exchange between region $p$ and other regions in season $s$ at time $t$
$f_{p,m,s,t}$	Power exchange of region $p$ with other regions via transmission lines of type $m$ in season $s$ at time $t$
$P_{p,j,s,t}^{ch}$	Charging power of storage system $j$ in season $s$ at time $t$ in region $p$ .
$P_{p,j,s,t}^{dch}$	Discharging power of storage system $j$ in season $s$ at time $t$ in region $p$
$P_{p,s,t}^{loss}$	Transmission power loss function due to power exchange of region $p$ with other regions in season $s$ at time $t$
$\delta_{p,s,t}^{heating}$	The electrified heating demand in time $t$ of season $s$ in region $p$ .

## 1- Introduction

The global transition toward renewable energy has accelerated in recent years, driven by mounting environmental concerns, including rising greenhouse gas emissions and local air pollution, coupled with finite fossil fuel reserves, rapid technological advancements, and declining costs of clean energy systems. Consequently, investment in renewable energy infrastructure has surged worldwide. However, the inherent intermittency and non-dispatchability of most renewable sources, particularly their dependence on weather conditions, pose significant operational challenges. These limitations have prompted the development of new regulatory frameworks and grid integration strategies to support aggressive renewable deployment.

Concurrently, in the energy demand sector, space heating and cooling loads exhibit strong temporal and climatic dependencies, mirroring the variability of renewable supply. In the residential and commercial sectors, these thermal loads constitute a major share of energy consumption, especially during seasonal peaks. Recent advances in heat pump technology have enabled the electrification of heating and cooling demands, creating new synergies with renewable electricity generation. Accurately quantifying these thermal loads at the building level is therefore critical, not only for optimizing local energy systems but also for shaping national electricity generation portfolios and facilitating a low-carbon energy transition.

Globally, the electrification of heating and cooling demand has emerged as a critical pathway for decarbonizing the residential sector. Recent studies underscore both the technical promise and socioeconomic complexity of this transition. In Texas, modeling by White et al. [1] reveals that full electrification via heat pumps could spike winter peak demand by 36% (12 GW), yet annual electricity consumption remains stable or declines due to superior cooling efficiency, simultaneously cutting CO<sub>2</sub> and NO<sub>x</sub> emissions by 4.1% and 5.8%, respectively. At the urban scale, Khosravani et al. [2] demonstrates that electrification increases annual electricity use by 28% and shifts peak load to winter (+49%), but coupling with hybrid renewable systems (HRES) under carbon pricing or subsidy regimes can optimize renewable penetration up to 60%.

In the European Union, Salim et al. [3] projects that meeting 2050 climate targets requires over 68% of residential heating to be supplied by electric heat pumps or boilers, a transition contingent on coordinated

policy implementation and accelerated building renovation. Critically, Sandoval et al [4] warns that without targeted interventions, renters may bear disproportionate costs if landlords opt for cheaper, inefficient resistance heating; however, policy tools like the U.S. Inflation Reduction Act rebates can make high-efficiency heat pumps economically viable even for landlords, emphasizing that upfront cost reduction, not utility rate reform, is the primary lever for equitable adoption.

Further, Hewitt et al. [5] examines the role of electrification, particularly through heat pumps, in decarbonizing space, water, and process heating. It highlights challenges related to electricity network capacity, cost, and operation of heat pumps, while emphasizing the role of thermal storage in demand-side management. A UK housing retrofit case study further illustrates practical solutions to mitigate network impacts.

Numerous studies have addressed the issue of meeting the heating and cooling demands through electrification and the use of renewable energy resources. In [6], the expansion of renewable energy resources for optimizing energy use in energy-intensive industrial sectors have been examined, and a linear programming model have been presented to estimate consumption across 12 industrial sectors in Iran. The researchers in [7] have focused on the uncertainty of renewable power generation and, have proposed an optimization model using robust optimization techniques for renewable energy development in Iran. Rezaei et al. [8] have investigated the development of renewable power plants to supply electricity and heat for residential sectors, providing economic analyses for scenarios where electricity is supplied solely from renewable sources and in combination with the grid power. The model has been simulated for a house in Tehran, and has been solved using the genetic algorithm.

To address seasonal shortages of electrical and thermal energy in various climates across Iran, Ahmadi-Kaliji et al. [9] employs the energy system modeling to advocate for renewable energy development as a solution. In [10], an evaluation of the potential and capacity utilization of renewable energy resources in Iran have highlighted the need for increased use of these resources. Yousefi et al. [11] have predicted energy demand in Iran using multi-criteria decision-making and have assessed the potential for renewable energy development in eastern Iran. Hasheni et al. Reference [12] presents an AI-driven method to estimate the potential electrified heating demand at the power transmission system level by combining cooling demand patterns derived from power consumption data and gas consumption data, leveraging the physical properties of buildings and machine learning techniques.

A robust chance-constrained optimization model had been developed in [13] to address power shortages in Iran, emphasizing the use of renewable energy and flexible loads as a solution. Hashemi et al. [14] have evaluated renewable energy resources in Iran based on operational data and statistical sources. They compare popular indices to compare the potentials of different renewable resources in different areas. In [15], demand supplying in the remote areas is analyzed by focusing on wind, solar, and battery technologies as solutions to reduce the energy poverty of these areas. The suitability of these technologies has been assessed using linear and nonlinear models. Sharifian et al. [16] examine the reduction of greenhouse gas emissions in Iran's energy system using the OSeMOSYS energy planning model. they emphasize the need for renewable energy development. In [17], the impact of emission constraints and water supply costs on the power generation expansion planning problem have been analyzed, and a plan for renewable energy development in Iran has been outlined based on real energy consumption data and potential for various energy sources. In [18], the machine learning techniques have been applied to analyze the renewable energy supply chain, providing policy recommendations tailored to Iran's conditions. Slocum et al. [19] have explored the transition from a hydrocarbon-based economy to a sustainable one through the development of renewable energy sources, including solar, wind, nuclear, and pumped hydro storage.

Majd et al. [20], have developed an electricity generation and transmission model for Iran energy system, with a focus on high renewable energy penetration. In [21], the use of solar systems for meeting heating, cooling, and hot water demands in residential buildings have been investigated using simulation tools and the hourly modeling to compare photovoltaic and thermal systems across different climates. The study has concluded with a levelized cost of energy (LCOE) analysis. In [22], three clean energy production structures have been proposed and their technical and economic performance have been evaluated. They have been based on ocean thermal energy conversion, wind turbines, and solar panels. Their performance has been assessed using real data from Bandar Abbas city. The adoption of new technologies to meet heating and cooling demands, aligned with the concept of electrification, have significantly impacted research in this field. For example, Yousefi et al. [23] have optimized energy consumption in buildings using heat pumps, demonstrating that gas consumption is completely eliminated and annual electricity consumption is reduced by 77 megawatt-hours in a real-world example in Tehran. This have been achieved through electrification and the use of renewable energy resources.

Recent studies have proposed a multi-period optimization model for the cost-effective design of energy systems that accounts for temporal variations in energy production and consumption. Simulation results from this research demonstrate that the combined utilization of solar energy and thermal storage systems leads to a substantial reduction in boiler capacity requirements [24]. Alirezai et al. [25] have analyzed an integrated cooling, heating, and desalination system for vertical farming in Bushehr, emphasizing the synergistic use of solar energy for simultaneous thermal and power generation. In [26], a simulation tool has been developed for modeling and analyzing thermal systems. The tool enables both static and dynamic simulations, providing capabilities for performance analysis of both district heating systems and decentralized heating systems. Yuan et al. [27] examines the current status, potential, and policy frameworks of China's district heating systems. The authors highlight the integration of renewable energy sources with waste heat recovery as a cornerstone for implementing fourth-generation district heating (4GDH) systems. They emphasize energy storage technologies as critical enablers for this transition while providing an in-depth analysis of the economic dimensions involved.

Berger et al. [28] evaluates the combined performance of renewable-based storage systems, including photovoltaic (PV) and solar thermal (ST) technologies, in comparison with various storage options such as subsurface water tanks and battery storage. The analysis examines system performance for both single-family and multi-family residential buildings in Switzerland. The research underscores the critical importance of selecting storage technologies that are optimally suited to local conditions and requirements. Yang et al. [29] investigates the potential of seasonal thermal energy storage (STES) for meeting heating demand, while analyzing its role in facilitating renewable energy integration within power systems and reducing greenhouse gas emissions. The study employs real operational data from China's energy sector to validate its findings. [30] introduces a new set of equations to model energy storage systems within the system planning problem, simplifying their computationally challenging operational constraints.

Novosel et al. [31] identifies centralized heating and cooling systems as an effective approach for improving system flexibility and accommodating intermittent renewables. The study utilizes the H2RES optimization framework [32], which combines annual planning cycles for infrastructure development with short-term operational assessments through energy dispatch modeling. Hashemi et al. [33] addresses system flexibility [34] in the context of combined electrical and thermal load supply. The study introduces various flexibility indices to optimize thermal demand fulfillment in the most cost-effective manner while adhering to flexibility constraints.

Although numerous studies have addressed the integration of renewable energy sources into heating and cooling supply infrastructures, several research gaps remain:

- Many studies have focused on small-scale applications, such as individual buildings or, at most, a single city.
- Thermal characteristics of buildings and climatic diversity have often been overlooked.
- Optimization models have generally failed to holistically address the simultaneous development of energy production, storage, and transmission, while seasonal and short-term demand variations are frequently neglected.
- In most cases, there has been insufficient sensitivity analysis regarding the impact of key technical and economic parameters, such as energy storage and transmission equipment costs, as well as transmission and distribution network losses, particularly at the national scale in geographically diverse countries like Iran.

Addressing current research gaps requires a comprehensive and integrated development framework with high temporal and spatial resolution. This study introduces an optimization model to determine the capacity and mix of renewable energy resources for meeting heating and cooling demand, alongside the optimal share of electrified heating across provinces. Heating and cooling demand is estimated using temperature profiles, building characteristics, and degree-day metrics at both national and regional scales. The model integrates electricity generation, storage, and transmission planning, while capturing seasonal and intra-day variations. Applied to Iran, it enables the identification of renewable technology portfolios, storage requirements, transmission needs, and provincial priorities for heating electrification. These are the Key Contributions:

- An integrated optimization model that jointly plans generation, storage, and transmission while accounting for heating and cooling electrification.
- Demand estimation based on building heat transfer and degree-day metrics across diverse climates.
- A multi-period modeling approach capturing seasonal and intra-day dynamics for improved flexibility.
- Identification of optimal heating electrification strategies by location and scale.

Section 2 reviews key metrics for evaluating renewable energy potential. Section 3 presents a novel framework for estimating heating and cooling demand, integrating building heat transfer physics, regional climate data, and heating/cooling degree days. Section 4, the core of this study, introduces a comprehensive optimization model that co-plans renewable generation, energy storage, and transmission infrastructure to cost-effectively electrify thermal demand. Section 5 validates the model using real-world data from Iran, with detailed scenario and sensitivity analyses. Section 6 concludes with policy-relevant insights and future research directions.

## **2- Evaluation of Renewable Energy Development Potential**

Wind and solar power are among the most prominent renewable electricity sources, yet their output is inherently dependent on environmental conditions, making regional potential assessment essential. Unlike fossil fuel-based plants, renewable resources cannot be relocated, and their generation is non-dispatchable. Two key performance indicators are the capacity factor, which measures the ratio of actual to potential annual energy generation (see Eq. (1)), and the capacity credit, which reflects the reliability of renewable capacity during different demand levels, particularly peaks (see Eq. (2)). For instance, while southern Iranian cities offer high solar potential due to longer daylight hours, elevated ambient temperatures reduce

photovoltaic efficiency, lowering the capacity factor. Capacity credit further illustrates the extent to which renewable installations can reliably substitute conventional thermal capacity.

$$Capacity\_factor_{k,p} = \frac{\sum_{h=1}^{h=8760} e_{k,p,h}}{8760} \quad (1)$$

$$Capacity\_credit_{k,p} = \frac{\sum_{h \in T^{peak}} e_{k,p,h}}{|T^{peak}|} \quad (2)$$

### 3- Space Heating and Space Cooling Demand

Temperature is the most influential environmental factor driving energy demand for space heating and cooling in buildings. Indoor thermal conditions are shaped by a combination of external and internal variables, including outdoor temperature, internal heat gains, solar orientation, wind exposure, and, most critically, the thermal properties of the building envelope, particularly wall materials.

To quantify this energy demand, the degree-day method remains one of the simplest and most widely adopted metrics. Heating Degree Days (HDD) are calculated by summing, over a given period, the daily deviations of mean outdoor temperature below a predefined heating threshold. Similarly, Cooling Degree Days (CDD) measure cumulative daily deviations above a cooling threshold. These indices, formalized in Eqs. (3) - (4), provide a robust proxy for estimating annual heating and cooling energy requirements, directly linking climatic variability to building energy performance.

$$HDD = \sum_{d=1}^{365} \max(T_d^{heating} - T_d, 0) \quad (3)$$

$$CDD = \sum_{d=1}^{365} \max(T_d - T_d^{cooling}, 0) \quad (4)$$

Naturally, cooling and heating demands arise during summer and winter seasons, respectively, and can be analyzed based on the environmental conditions of different cities and diverse climatic zones. By integrating the aforementioned relationships and the physical characteristics of buildings, primarily the material composition of the building envelope, the required heating and cooling energy can be calculated as Eqs (5) - (6). In this formulation, heat transfer through various building envelopes and their respective surface areas are accounted for. Additionally, the efficiency of heating and cooling systems is incorporated into determining the energy required to operate them.

$$HL = \frac{24 * HDD \sum_i a_i u_i}{\eta^h} \quad (5)$$

$$CL = \frac{24 * CDD \sum_i a_i u_i}{\eta^c} \quad (6)$$

Typically, a building's heat loss is represented as an approximate coefficient dependent on the type of insulation used and is expressed per unit floor area of the building. In other words, the summation  $\sum_i u_i a_i$  is replaced by  $A \cdot U$ , where  $A$  denotes the building area and  $U$  represents the equal heat transfer coefficient. Additionally, the efficiency of cooling systems, such as air conditioners or evaporative coolers, is quantified using the Coefficient of Performance (COP). Finally, assuming the durations of the summer and winter periods are  $\Delta^s$  and  $\Delta^w$ , respectively, the power required to meet heating and cooling demands can be expressed by the Eqs (7) - (8).

$$P^h = \frac{24 \times HDD \times A \times U}{\eta^h \Delta^w} \quad (7)$$

$$P^c = \frac{24 \times CDD \times A \times U}{COP^c \Delta^s} \quad (8)$$

## 4- Renewable Energy Development Optimization Model

Determining the deployment capacity of various renewable energy sources and their installation locations depends on multiple technical and economic factors, necessitating the definition and solution of an optimization model. In this section, we outline the objective function and constraints of this optimization framework.

### 4-1 Objective Function

The objective function of the optimization model, that is depicted in Eq. (9) involves minimizing the total costs associated with constructing power generation technologies, energy storage systems, and electricity transmission infrastructure, as well as operational expenditures.

$$\min_{P_{p,k,s,t}, X_{p,k}^G, X_{p,j}^{stg}, X_{p,m}^l} Z = \sum_{p,k} Z^{Gen} (X_{p,k}^G) + \sum_{p,j} Z^{stg} (X_{p,j}^{stg}) + \sum_{p,m} Z^{Tr} (X_{p,m}^l) + \sum_{p,k,s,t} Z^{operation} (P_{p,k,s,t}) \quad (9)$$

The cost of developing renewable power plants is expressed by equation Eq. (10), which accounts for the technology's price, installed capacity, and the annualization factor for capital costs. This cost is integrated into the objective function:

$$Z^{Gen} (X_{p,k}^G) = \sum_k IC_k^{Gen} X_{k,p}^G \frac{r(1+r)^{n_k}}{(1+r)^{n_k} - 1} \quad (10)$$

The cost of expanding transmission infrastructure around each region is incorporated into the objective function using equation Eq. (11). Depending on the transmission technology type, installed capacity, network length, and the annualization factor for costs, these expenses are reflected in the objective function.

(11)

The cost of deploying energy storage systems in each region is included in the objective function as shown in Eq. (12). This cost depends on the installed capacity, technology price, and the annualization factor for capital costs.

$$Z^{stg} (X_{p,j}^{stg}) = \sum_j IC_j^{stg} X_{p,j}^{stg} \frac{r(1+r)^{n_j}}{(1+r)^{n_j} - 1} \quad (12)$$

In addition to capital costs for power plants and transmission networks, operational expenditures (OPEX) for production, storage and transmission facilities during operational periods are among the most significant expenses. The power generated by production technologies contributes to operational costs, which are formulated as Eq. (13).

$$Z^{operation} (P_{p,k,s,t}) = OC_k P_{p,k,s,t} \quad (13)$$

### distance estimation

Accurately determining the costs of transmission network development requires incorporating load flow models, which significantly increases the complexity of the optimization framework. To mitigate this complexity, a distance coefficient is defined for each candidate installation zone, representing its relative

proximity to other zones. Based on Eq. (14), this coefficient for each zone is calculated as the arithmetic mean of its distances to all other zones.

$$D_p = \frac{\sum_{p'=1}^N dist_{p,p'}}{N} \quad (14)$$

#### 4-2 Optimization Model Constraints

The installed renewable capacity in each region and the possibility of energy transfer from other regions are the two primary factors in meeting heating and cooling demands. These are modeled as the equation Eq. (15).

$$\sum_k P_{p,k,s,t} = F_{p,s,t} + \sum_j (P_{p,j,s,t}^{ch} - P_{p,j,s,t}^{dch}) + P_{p,s,t}^{loss} (F_{p,s,t}) + L_{p,s,t}^{cooling} + \delta_{p,s,t}^{heating} \quad (15)$$

As shown in Eq. (16), the electrified heating demand in each province has to be lower than its total heating demand. In addition, a part of total heating demand should be supplied through the electrification of the heating systems, as depicted in Eq. (17).

$$\delta_{p,s,t}^{heating} \leq L_{p,s,t}^{heating} \quad (16)$$

$$\sum_p \delta_{p,s,t}^{heating} \geq \alpha^e \sum_p L_{p,s,t}^{heating} \quad (17)$$

If the heating electrification strategy is predetermined independently for each province, Eq. (18) is applied in the model instead of Eq. (17).

$$\delta_{p,s,t}^{heating} \geq \alpha_p^e L_{p,s,t}^{heating} \quad (18)$$

In addition to transmission infrastructure costs, long-distance electricity transfer incurs losses, which are a function of transmitted power and network length. These losses must be compensated by generation resources, increasing both capital and operational costs. The losses are modeled linearly and equally distributed between the source and destination regions. Based on the Eqs. (19)-(20), regardless of the direction of power exchange between region  $p$  and other regions, losses are calculated using the average distance of  $p$  to other zones and the total exchanged power. Half of these losses are allocated to region  $p$ .

$$P_{p,s,t}^{loss} \geq 0.5 \rho^{loss} D_p F_{p,s,t} \quad (19)$$

$$P_{p,s,t}^{loss} \geq -0.5 \rho^{loss} D_p F_{p,s,t} \quad (20)$$

As depicted in Eq. (21), the power generated by each power generation technology is limited by its installed capacity and the regional capacity factor in each time period.

$$P_{p,k,s,t} \leq X_{k,p} CF_{p,k,s,t} \quad (21)$$

The power exchange between a region and its adjacent zones is constrained by the initial and installed transmission capacities around the region, as depicted in Eqs. (22)-(24).

$$F_{p,s,t} = \sum_m f_{p,m,s,t} \quad (22)$$

$$f_{p,m,s,t} \leq X_{p,m}^l + X_{p,m}^0 \quad (23)$$

$$-f_{p,m,s,t} \leq X_{p,m}^l + X_{p,m}^0 \quad (24)$$

While the simplified transmission network model does not explicitly define the source and destination of power transfers between regions, the total power exported from a region must equal the total power imported into other regions, as formulated in **Error! Reference source not found.**

$$\sum_p F_{p,s,t} = 0 \quad (25)$$

The charging and discharging rates of storage systems are bounded by their installed capacity. Storage capacity is typically expressed in kWh, but the charge/discharge rate also significantly impacts system performance and cost. Assuming average daily charge/discharge rates, the energy charged or discharged per period is constrained by the installed capacity, as depicted in Eqs. (26) - (27).

$$P_{p,j,s,t}^{ch} \Delta_{p,s,t} \leq X_{p,j}^{stg} \quad \forall t \in \{t^{day}, t^{night}\}, \forall s \in \{s^{summer}, s^{winter}\} \quad (26)$$

$$P_{p,j,s,t}^{dch} \Delta_{p,s,t} \leq X_{p,j}^{stg} \quad \forall t \in \{t^{day}, t^{night}\}, \forall s \in \{s^{summer}, s^{winter}\} \quad (27)$$

For storage systems operating on a daily cycle, the total energy charged and discharged within a 24-hour period must balance, as expressed in Eq. (28).

$$\sum_t (P_{p,j,s,t}^{dch} \Delta_{p,s,t} - P_{p,j,s,t}^{ch} \Delta_{p,s,t}) = 0 \quad (28)$$

## 5- Simulation

This section applies the proposed model to real-world data from Iran, a geographically vast country with diverse climatic zones and significant renewable energy potential, particularly in solar and wind resources. While Iran possesses substantial oil and gas reserves, it also holds untapped opportunities for renewable energy development.

### 5-1 Regional Potential for Renewable Energy Development in Iran

According to solar radiation geographic maps, Iran possesses numerous regions with high potential for solar power plant expansion. A large number of sunny days throughout the year, proximity to the equator, and favorable temperature conditions make the central and southern provinces of Iran particularly suitable for the expansion of solar energy infrastructure. Fig. 1 illustrates the range of hourly capacity factors for solar and wind power plants over a one-year period in each province. Each box represents the statistical distribution of hourly solar (Fig. 1.a) or wind (Fig. 1.b) capacity factors for a given province over the course of a full year (8,760 hours). The secondary y-axis indicates the annual average capacity factor for each province. The data for each province are based on simulations of photovoltaic panel and wind turbine performance in sub-regions of that province, utilizing data sourced from [35], [36]. As depicted in Fig. 1.a It can be observed that the average annual capacity factor of solar panels in provinces such as Chaharmahal and Bakhtiari, Fars, and Kerman exceeds 0.22, and in many other provinces, this value is above 0.20. The range of hourly capacity factors across provinces is wide and is well captured by the boxplot shown.

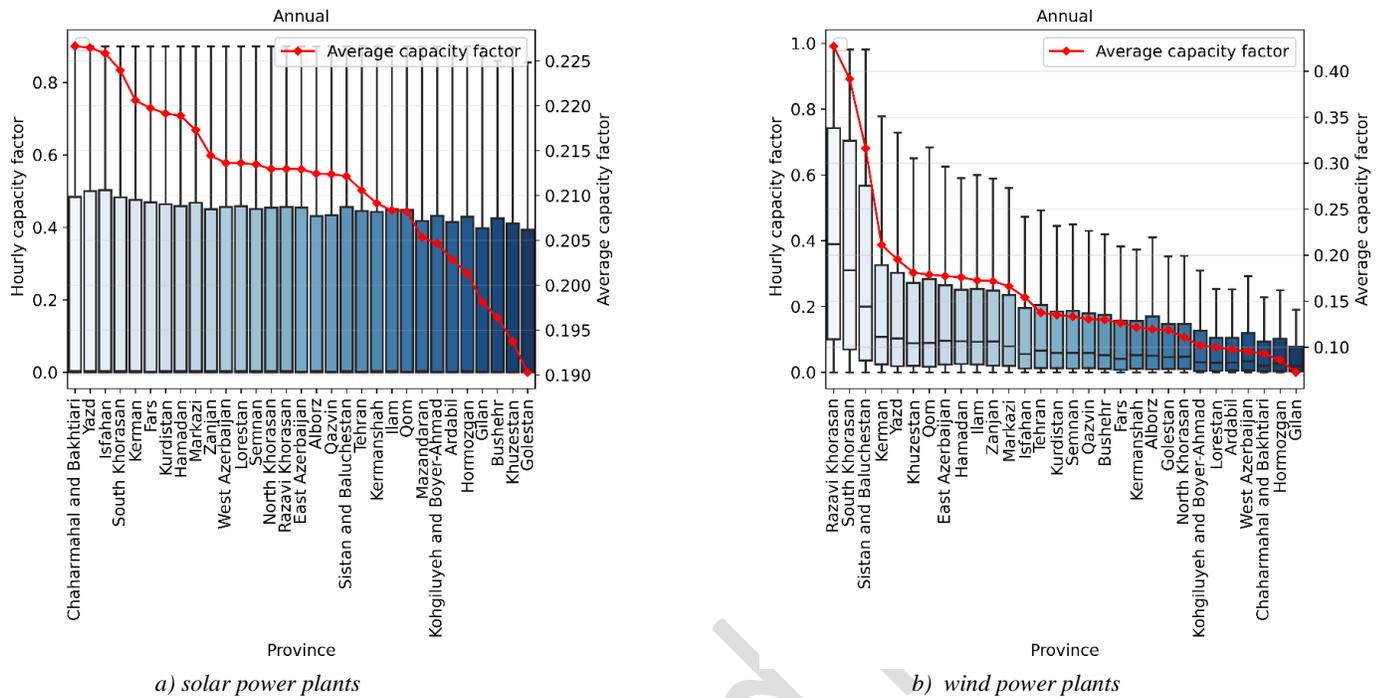
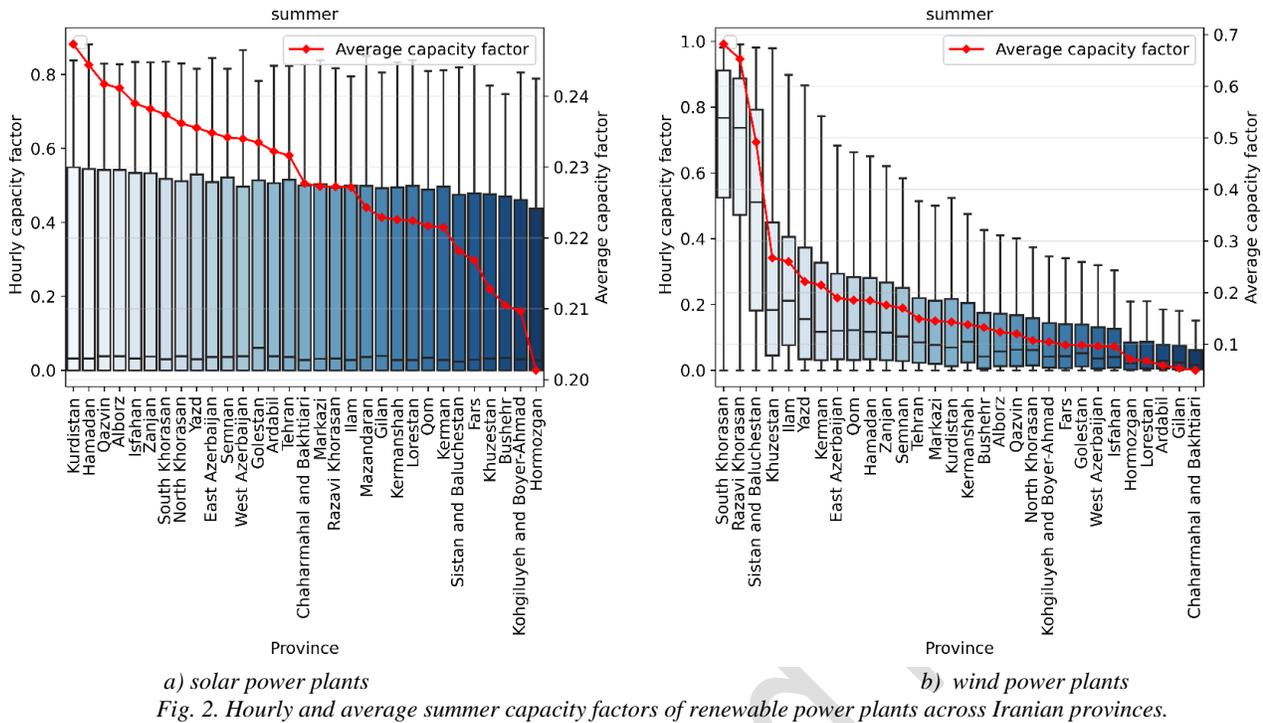


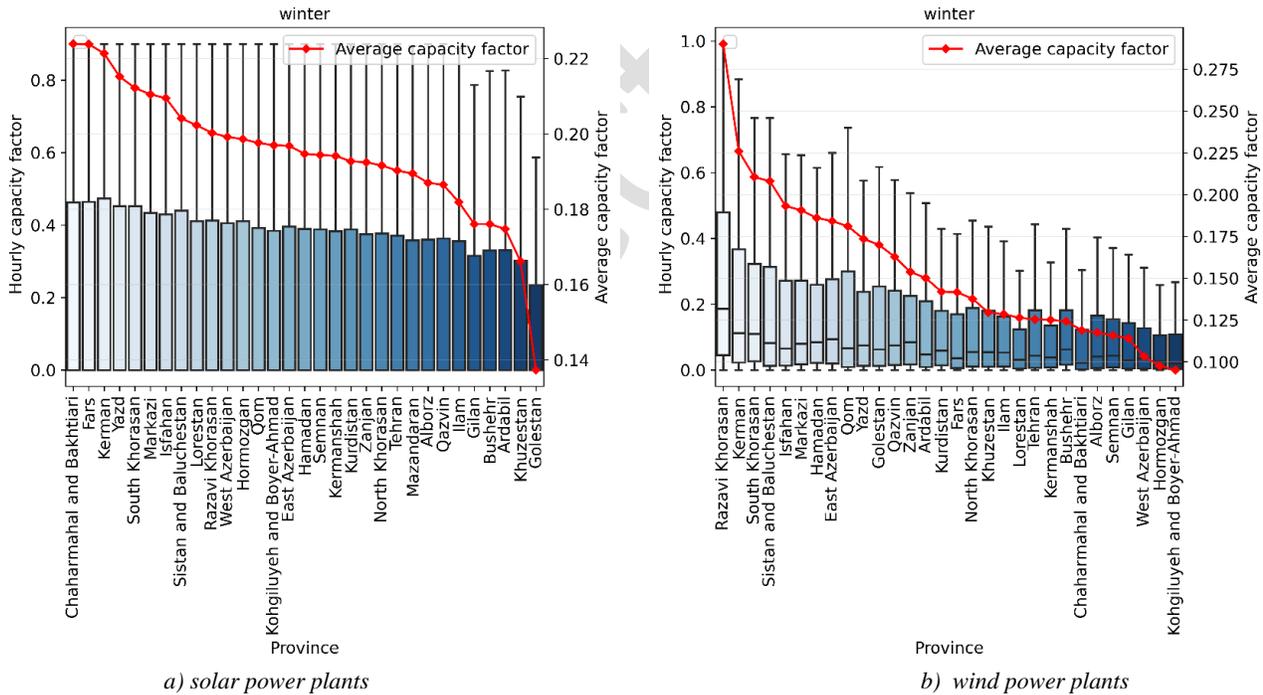
Fig. 1. Hourly and average capacity factors of renewable power plants across Iranian provinces.

Provinces such as Razavi Khorasan, South Khorasan, Sistan and Baluchestan, and Kerman exhibit the highest wind energy potential. However, a comparison with solar energy potential reveals that, overall, solar power development potential across provinces exceeds that of wind.

A separate analysis of renewable power plant performance during warm and cold seasons is critical, as electricity generation in these periods is predominantly allocated to meeting cooling and heating demands, respectively. Fig. 2 and Fig. 3 present this seasonal comparison. Note that the hourly capacity factor data used in each figure corresponds exclusively to either the warm or cold season.



a) solar power plants  
 b) wind power plants  
 Fig. 2. Hourly and average summer capacity factors of renewable power plants across Iranian provinces.



a) solar power plants  
 b) wind power plants  
 Fig. 3. Hourly and average winter capacity factors of renewable power plants across Iranian provinces.

As evident, the performance of both wind and solar power plants is significantly better during the summer compared to the winter. However, the decline in wind power capacity factors during winter is particularly pronounced, with some of the high-potential provinces experiencing reductions to nearly half, or even less, of their summer values. In contrast, the decrease in solar power capacity factors during winter is relatively

moderate, averaging around 10%. In summer, provinces located at higher latitudes tend to exhibit better solar capacity factors, primarily due to lower ambient temperatures that enhance photovoltaic efficiency. Nonetheless, this phenomenon is not solely temperature-dependent; other factors, such as longer daylight hours, also contribute. Conversely, in winter, provinces situated at lower latitudes perform better in terms of solar energy production. In this season, temperature plays a less critical role, while shorter daylight hours and reduced sunshine duration become more influential factors.

### 5-2 Space Heating and Cooling Energy Demand in Iran

Seasonal, monthly, and daily temperature fluctuations shape the heating and cooling energy demand across provinces. As previously discussed, Heating Degree Days (HDD) and Cooling Degree Days (CDD) are indicators used to estimate annual heating and cooling demands based on temperature data. The values of these indicators across different provinces are presented below in Fig. 4. A base temperature of 18 °C for HDD and 24 °C for CDD has been considered based on [31], which refer to outdoor air temperatures. It can be observed that in most provinces, HDD values exceed CDD values, indicating a generally higher demand for heating. However, in provinces such as Khuzestan, Bushehr, Hormozgan, and Sistan and Baluchestan, CDD values are significantly higher than in other regions, reflecting substantial cooling requirements in these warmer climates.

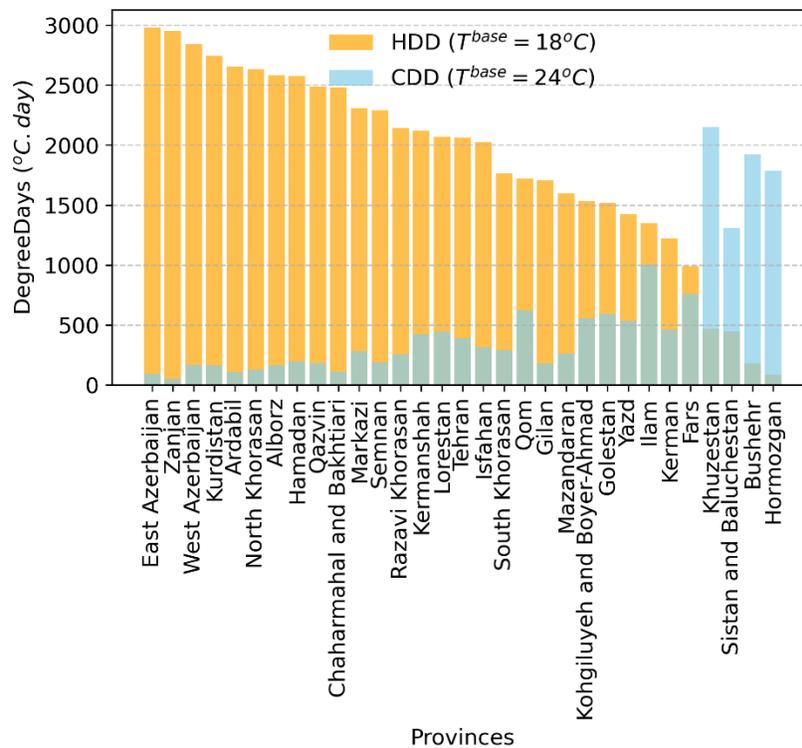


Fig. 4. Annual Heating Degree Days (HDD) and Cooling Degree Days (CDD) across Iranian provinces

To estimate the cooling and heating loads for each province, the approximate demand per building, calculated using Equations (7) and (8), is multiplied by the estimated number of residential and commercial buildings in each province. This number is assumed to be proportional to the population of the province. Building areas vary significantly across provinces; in provincial capitals, residents typically live in smaller apartments, while in smaller towns, houses generally have larger floor areas. Using a uniform and identical heat loss coefficient (HLC) for all buildings compromises the validity of the results obtained from the

model. Therefore, the HLC for buildings located in different provinces are assumed to vary based on [38], and are as shown in Fig. 5.

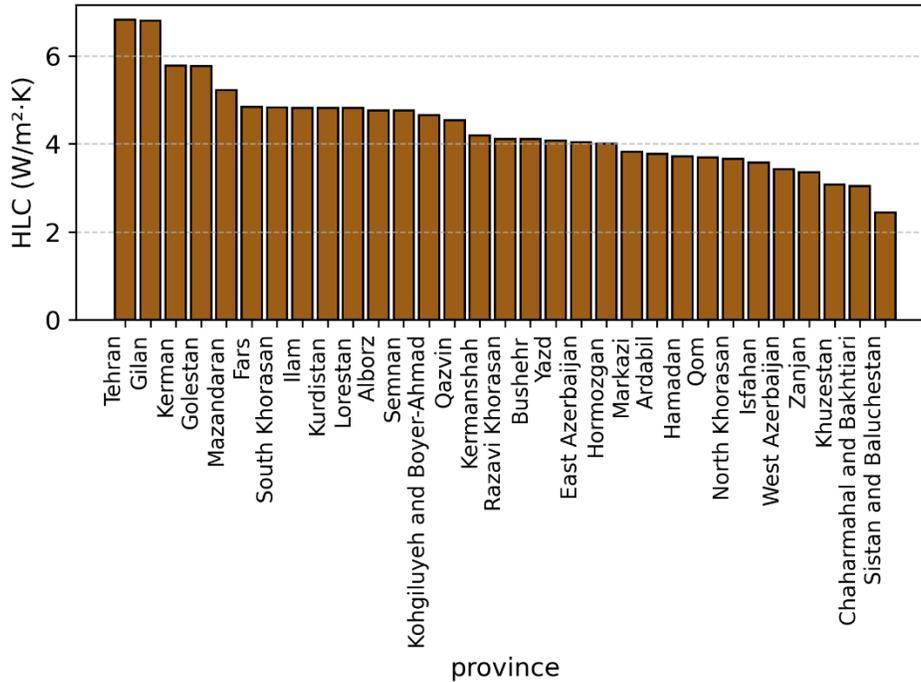


Fig. 5. Heating loss coefficient of buildings in provinces of Iran [38]

Natural gas is the primary source for meeting heating demand, and gas heaters with an average energy efficiency of about 75% are commonly used. Although the electrification of heat supply would result in varying electricity demand depending on the heating system type, this study assumes the use of electric heaters with an efficiency of approximately 95%, as they are significantly more affordable than alternative systems.

Regarding cooling systems, the prevailing cooling technology used in each province is considered. In dry provinces, evaporative coolers are typically used, while in humid provinces, air conditioners are more common. In provinces with moderate humidity levels, a combination of both technologies is assumed. The Coefficient of Performance (COP) is assumed to be 9 for evaporative coolers and 2 for air conditioners. For provinces with moderate humidity, the average of these two COP values is used. It is also assumed that the summer and winter seasons last for four and five months, respectively. The table below summarizes the input data used in the optimization process.

Table 1: Assumed coefficients of performance (COP) for cooling systems and heating system efficiencies across different climate types

Climate Type	Efficiency of Heating Systems	COP of Cooling Systems
Arid (Dry)	0.9	9.0
Humid	0.9	2.0
Moderate	0.9	5.0

By applying the aforementioned values and using equations (7) and (8), the average electricity demand required to meet the heating and cooling loads across provinces, during the cold and warm seasons, respectively, is illustrated in Fig. 6.

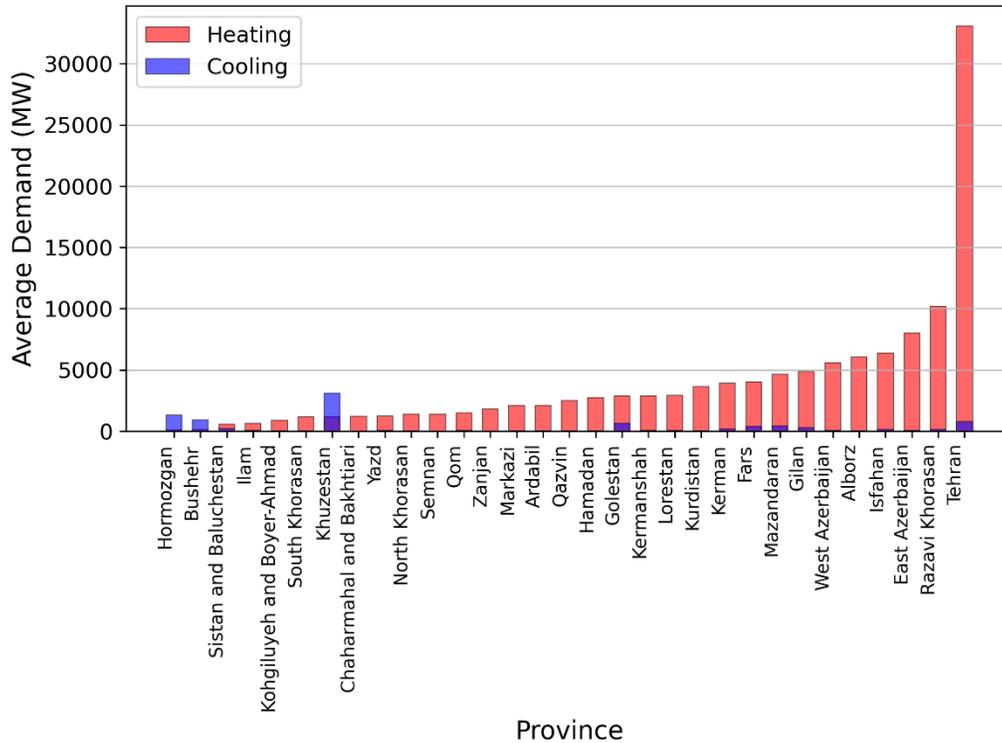


Fig. 6. Average heating and cooling demand across Iranian provinces, respectively in winter and summer

### 5-3 Economic Parameters

The most significant economic parameter associated with renewable power plants is their capital cost, as their operational and maintenance costs are relatively low. In Iran, the average power loss in the electricity distribution network is approximately 11%, while the transmission network incurs about 4% losses. Accordingly, a total loss factor of 15% is assumed in this study, with actual losses adjusted based on the distance factor assigned to each province. Furthermore, the cost of grid expansion is defined and applied per unit of capacity and line length. The relevant data are presented in the table below.

Table 2: Capital and operating costs assumed for solar and wind power plants, as well as for electricity transmission network expansion

Item	Solar Power Plant (\$/kW)	Wind Power Plant (\$/kW)	Transmission Network (\$/kW/km)
Capital Cost	400	800	0.04
Operating Cost	0	0	0

To investigate different aspects of the problem, three simulation cases are considered as follows. In Case1, a year is classified into only two seasonal periods: winter and summer. Also, the electrification coefficient of  $\alpha^e$  is independently applied to each province. In Case2, more details are considered and a year is classified not only into winter and summer periods but also into daytime and nighttime hours within each season. In this case, the electrification strategy is similar to that of Case1. In Case3, four operational periods

are modeled in a year, and the electrification coefficient is applied to the total heating demand of Iran, instead of applying it to all the provinces, independently. Table 3 summarizes the features of the simulation cases. As can be observed, in all the simulation cases, the electrification factor is considered 0.2.

Table 3: Properties of simulation cases

	<b>Operational periods</b>	<b>Electrification strategy of space heating demand</b>
<b>Case1</b>	Two periods: one for typical summer day, one for typical winter day	Applying $\alpha_p^e = 0.2$ to heating demand of <u>each</u> province. Equations: (1)-(16) & (18)-(28)
<b>Case2</b>	Four periods: two for summer day (daytime and nighttime), two for winter day (daytime and nighttime)	Applying $\alpha_p^e = 0.2$ to heating demand of <u>each</u> province. Equations: (1)-(16) & (18)-(28)
<b>Case3</b>	Four periods: two for summer day (daytime and nighttime), two for winter day (daytime and nighttime)	Applying $\alpha_p^e = 0.2$ to <u>total</u> heating demand of Iran. Equations: (1)-(17) & (19)-(28)

The proposed optimization model is applied to the real data of the renewable potentials, and the heating and cooling demands of Iran's provinces, using the optimization package of PYOMO in python. The following sections represent the results obtained from applying the optimization model under these simulation cases.

#### 5-4 Results of Case1

By applying the optimization model to the provided data, the optimal capacity and location for the deployment of renewable energy technologies are determined. Fig. 7 illustrates the selected capacities for solar and wind power plants. As shown, the entire selected capacity is allocated to solar power. To prevent excessive concentration of development in a single region, a maximum deployment cap of 50,000 MW per province has been imposed. The provinces of Fars, and Chaharmahal and Bakhtiari account for the largest shares of solar power development. Comparing these results with the average capacity factor of solar power plants during the winter season reveals that these two provinces exhibit the highest capacity factors in winter, thus making them top priorities for solar power deployment. In addition to the capacity factor of solar power plants, the volume of the heating demand is another important measure to allocate the solar power capacity, as it has no need to network expansion and has the benefit of lower power loss. Razavi Khorasa, East Azerbaijan, Isfahan and West Azerbaijan are some of such provinces. The highest network capacity is needed around Chaharmahal and Bakhtiari, and Fars, as the main solar power generation resources, and Tehran and Khuzestan, as the main power demand provinces.

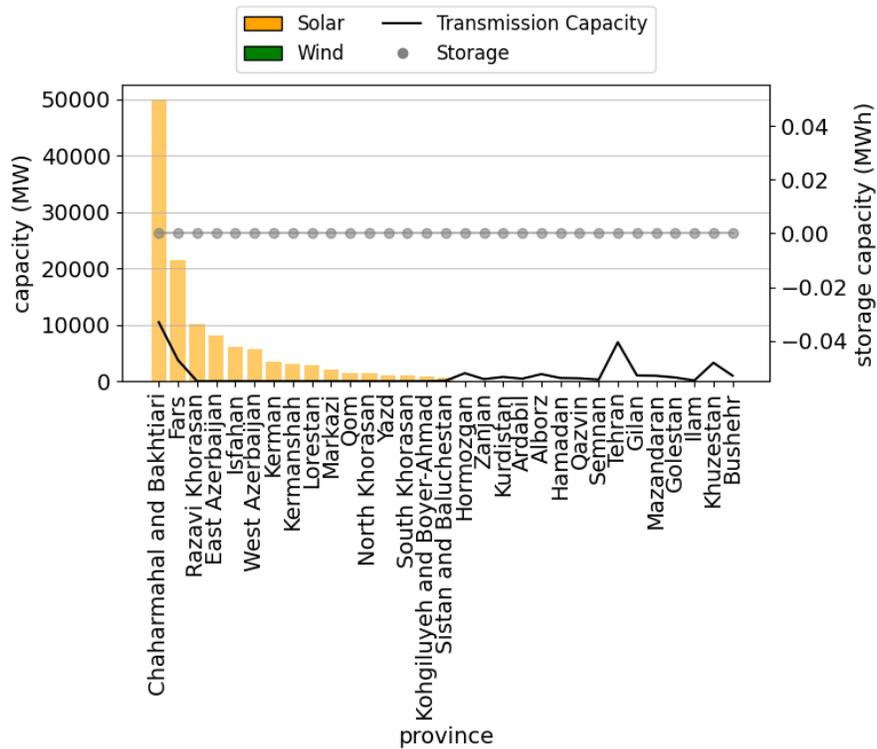


Fig. 7. expansion capacity results in each province under Case 1 optimization scenario

### 5-5 Results of Case2

The installed capacities of various renewable energy sources, storage systems, and transmission networks in this case are depicted in Fig. 8. In this case, modeling the night-time hours of summer and winter days, in which the installed solar power capacity is unavailable, forces to install energy storage units along with the installation of solar power plants. So, expansion of solar power plants requires high investment costs. The biggest power capacity is related to the wind power capacity installed in Razavi Khorasan, that has no need to the energy storage units. A considerable part of this capacity supplies the heating and cooling demand of the other provinces. So, the biggest transmission capacity should be installed around this province, as depicted in Fig. 8. Generally, the installed energy storage capacity of the provinces is in proportion to their installed solar power capacities, to supply their night demand. However, in Chaharmahan and Bakhtiari, lower energy storage capacity installed in the proportion of the installed solar power plants. As, most of this solar capacity supplies the power demand of the other provinces. In addition, there are some provinces such as Golestan, Ardabil and Gilan, in which the energy storage capacity is installed without installation of the solar power plants. These provinces have low solar capacity factor, and import power from other provinces. In days of winter, they store a part of the imported power to supply their night electrified heating power demand. Although, their required energy storage capacity can be installed in the power exporting provinces, it may need more storage capacity to supply the power transmission losses.

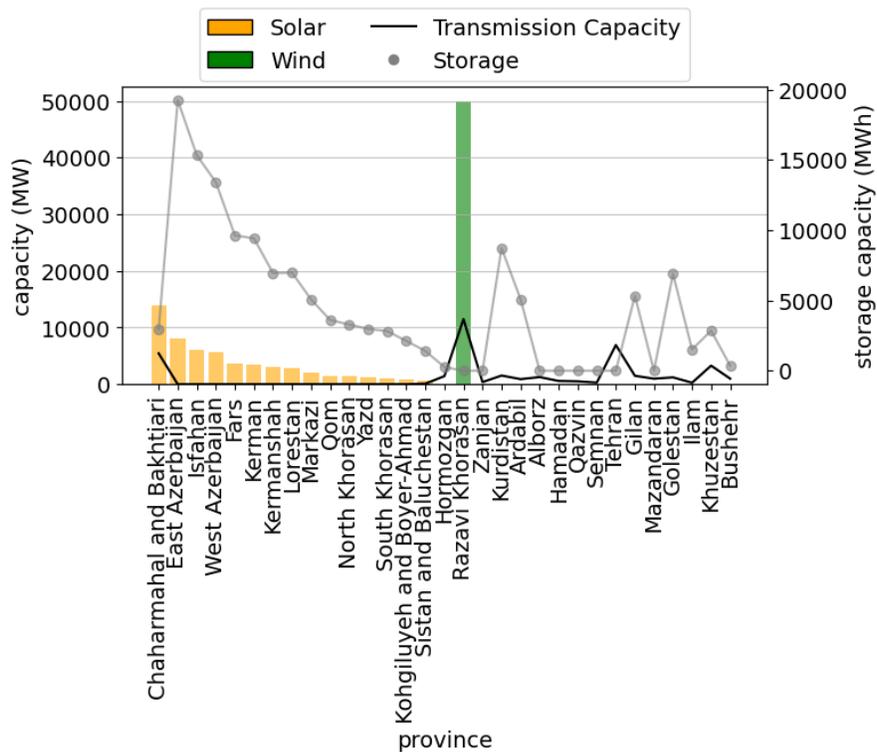


Fig. 8 Installed capacity of renewable resources, energy storage systems and power transmission network in each province under Case 2 optimization scenario

The operational pattern of the installed power generation, transmission and storage capacities has been depicted in different operation periods, as depicted in Fig. 9. During the summer, the electricity consumption of the provinces of Khuzestan, Hormozgan, and Bushehr, being the largest consumers of cooling energy, is entirely met through imported energy. During the daytime, the main energy sources are solar and wind power plants respectively located in Chaharmahal and Bakhtiari and Razavi Khorasan, while at night, energy is supplied by wind power generation in Razavi Khorasan and energy storage systems located in different provinces. As can be seen in the figure, a significant portion of the developed capacity of storage facilities and transmission networks in the provinces is used in the winter season. This is because the thermal demand of the provinces is generally greater than their cooling demand, and also because in most provinces the developed solar capacity covers the cooling needs of the province in the summer season, and the need for energy transmission is less. During the summer, the wind power plants developed in Razavi Khorasan are utilized exclusively for nighttime supply. Most of their production is transmitted to major consumption centers in the south. During the day, wind farms reduce their power generation, due to the high output from solar power plants located closer to the consumption areas. In daytime of winter, energy storage systems across various provinces are primarily in charging mode. Their energy supply sources include local solar power generation and electricity imported through the transmission network. The stored energy is then used at night, leading to minimal transmission network loading during this period, as local resources, mainly the discharging of storage systems, are sufficient to meet provincial energy demands. The wind power capacity of Razavi Khorasan, mainly supplies the local heating demand and the heating demand of Tehran, in winter.

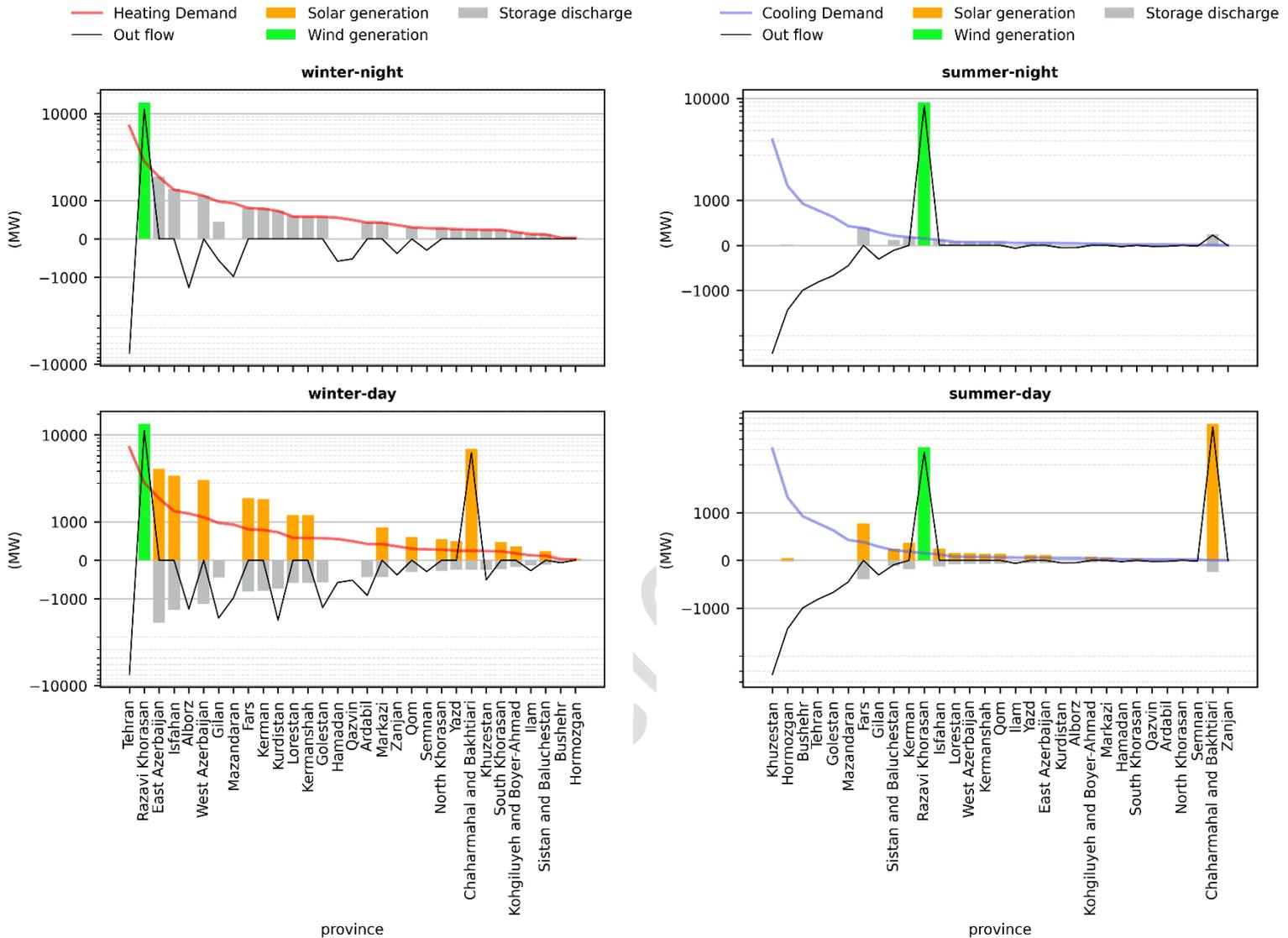


Fig. 9 Operation pattern of renewable energy sources, transmission network, and energy storage systems across different operational periods

The technology of energy storage systems is evolving, and a significant reduction in their prices is not unlikely. Fig. 10 illustrates the installation of renewable energy sources and storage systems under different price assumptions for storage systems. The highest sensitivity is observed within the price range of \$100 to \$150 per kilowatt-hour. As the price decreases within this range, solar power plants become the primary energy source for heating and cooling systems, leading to the substantial expansion of energy storage systems. The sensitivity of the generation mix to the price of storage is clearly greater than its sensitivity to transmission network parameters, such as the cost of line construction and losses. Variation of line price in the range 0.1-0.4 (\$/km/MW) can change the generation mix. In addition, the most sensitivity of the generation mix to the line loss is in the loss range of 16-17.5%.

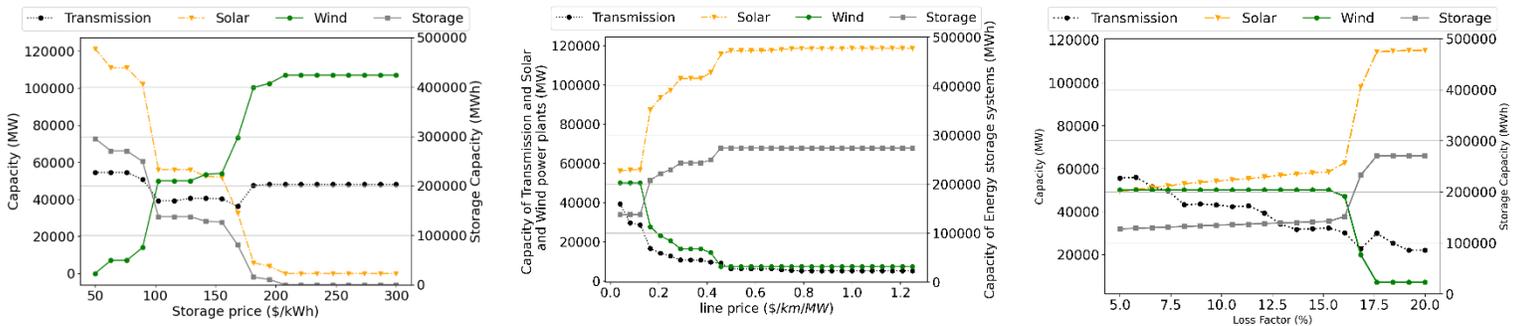


Fig. 10 Sensitivity analysis of the generation mix to the price of energy storage systems, the cost of transmission network construction, and the transmission network loss coefficient, in simulation case 2.

### 5-6 Results of Case3

In this simulation case, a total of 20% of the country's heat demand is to be electrified. Therefore, in addition to determining an optimal mix of energy generation, transmission, and storage, another key decision variable arises: the appropriate allocation of heat electrification capacity across provinces. Fig. 11 illustrates that only certain provinces have been selected for heat electrification. These selected provinces generally exhibit favorable renewable energy capacity factors and possess the potential for locally meeting the electrified heat demand.

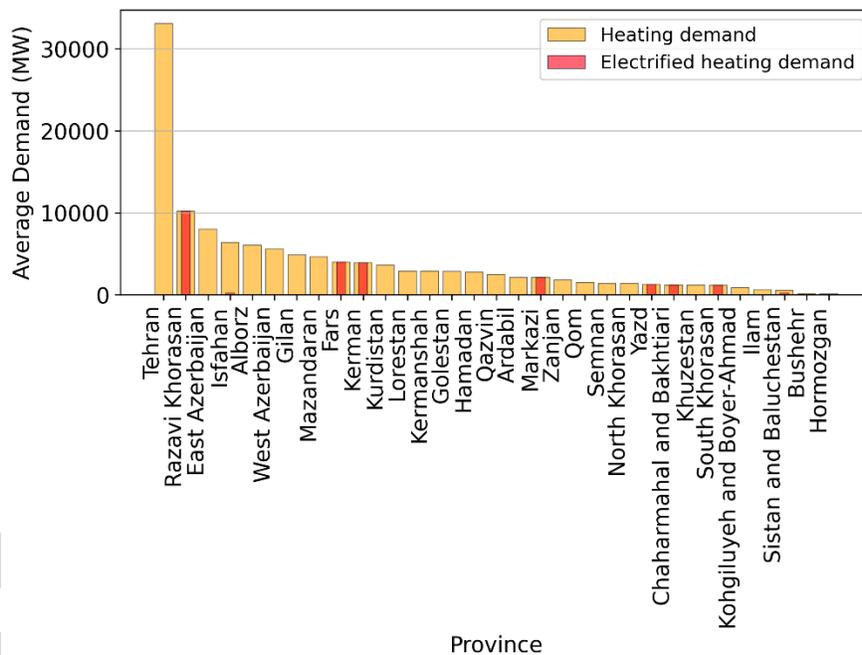


Fig. 11 The share of provincial heat demand electrification, assuming a 20% electrification rate, in simulation scenario 3.

Fig. 12 illustrates the optimal capacity expansion of energy generation, storage, and transmission infrastructure. It can be observed that renewable energy expansion is recommended precisely in those provinces where a portion or the entirety of the heat demand has been electrified.

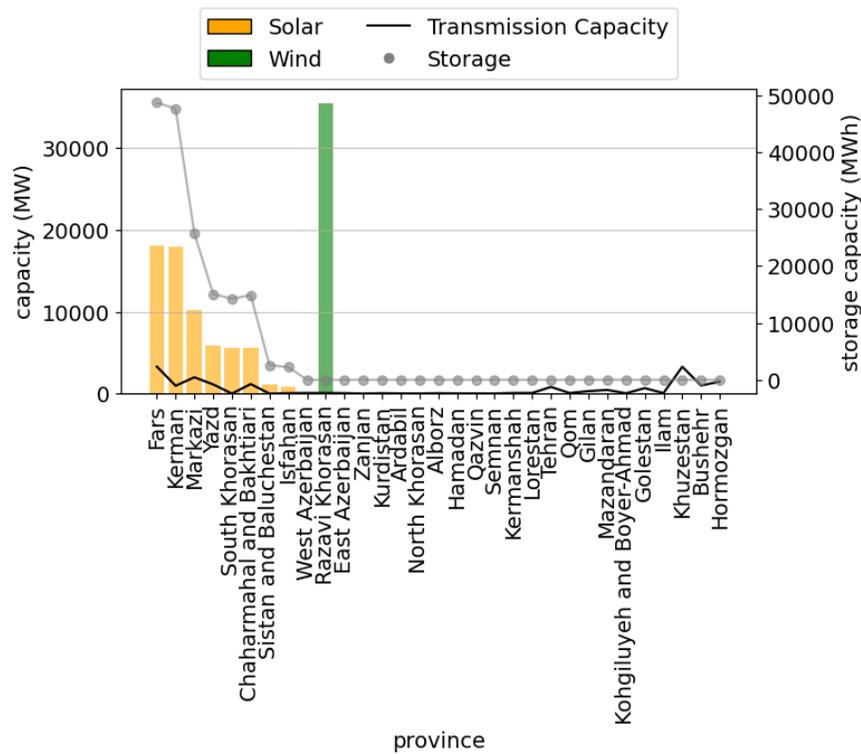


Fig. 12 Installed capacity of renewable resources, energy storage systems and power transmission network in each province under Case 3 optimization scenario

Fig. 13 depicts the seasonal operational patterns of renewable resources. In winter, provincially deployed solar plants meet daytime heating demand and charge storage systems with surplus energy for nighttime use; wind power further supports both day and night loads, enabling near-complete provincial self-sufficiency with minimal inter-provincial exchange. In summer, cooling demand—being geographically dispersed—relies primarily on solar and storage, but requires extensive transmission infrastructure to distribute energy from resource-rich provinces to nationwide demand centers.

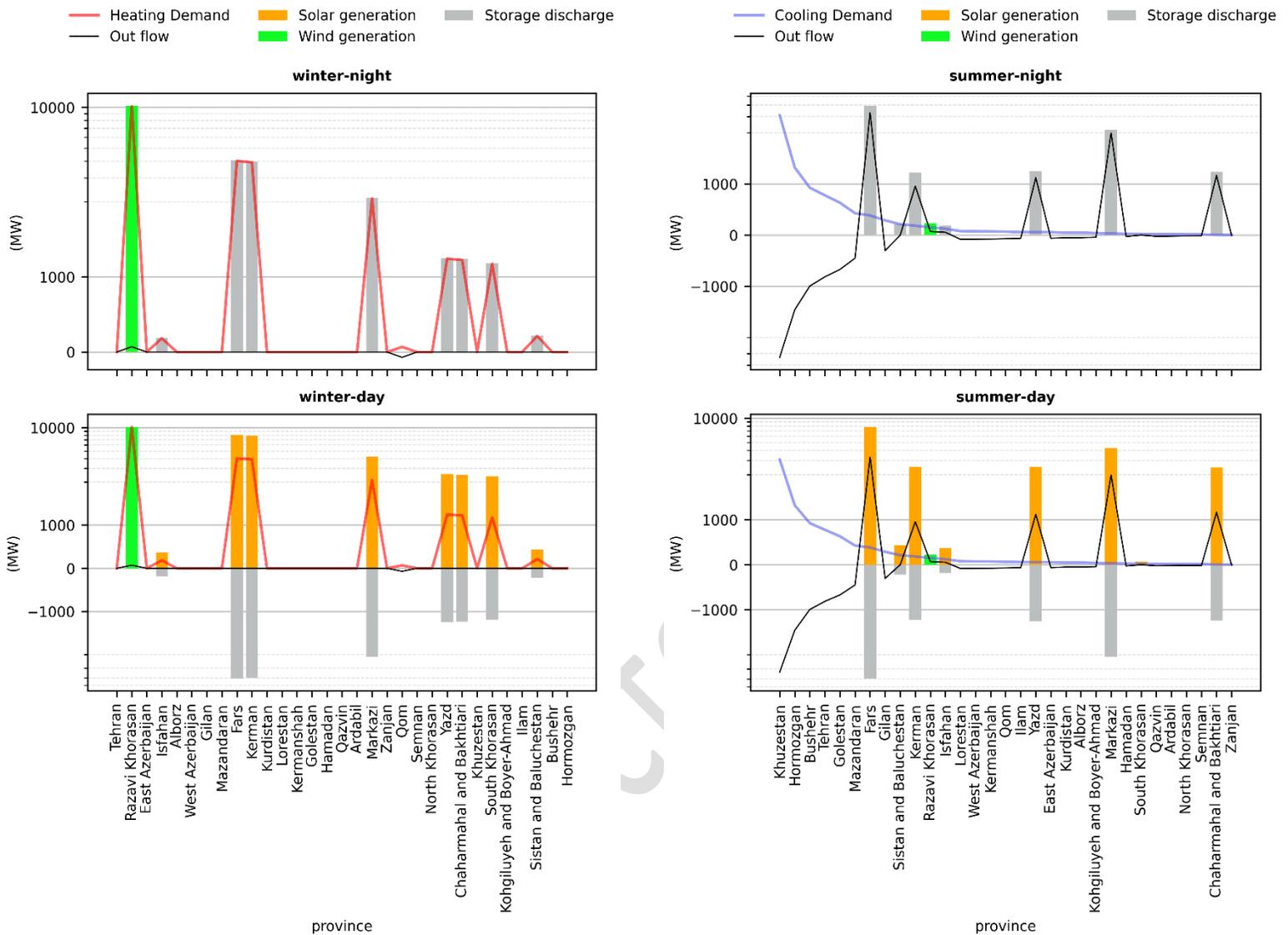


Fig. 13 Operation pattern of renewable energy sources, transmission network, and energy storage systems across different operational periods in case 3

As shown in Fig. 14 (Case 3), the expansion plan for generation, transmission, and storage is most sensitive to energy storage costs. Since heating electrification is allocated to enable predominantly local supply, inter-provincial power flows, and consequently, the impact of transmission investment costs and loss factors, are minimized. Nevertheless, network losses exert a stronger influence than transmission capital costs: higher losses not only increase operational waste and generation expenses but also necessitate additional investment in generation and storage capacity to compensate for energy dissipation.

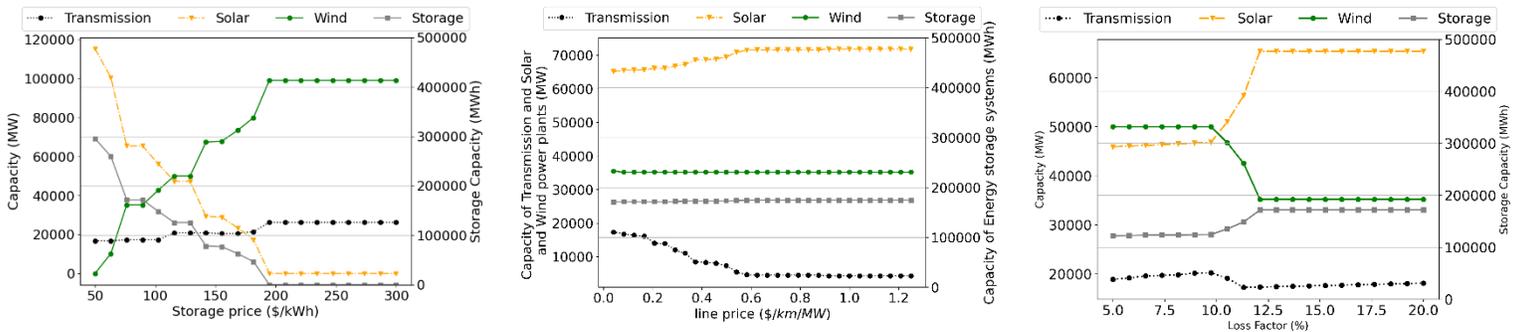


Fig. 14 Sensitivity analysis of the generation mix to the price of energy storage systems, the cost of transmission network construction, and the transmission network loss coefficient, in simulation case 3.

While previous simulations assumed 20% national heat electrification, Fig. 15 presents a heatmap ranking provincial electrification priority across varying levels. Provinces with high renewable potential, such as Razavi Khorasan, Chaharmahal and Bakhtiari, and Fars, are prioritized, as they enable cost-effective, locally supplied electrified heating. In contrast, provinces like Ardabil and Bushehr, with limited renewable resources, rank lowest; electrifying heat demand there would necessitate costly transmission expansion and incur high losses, reducing overall economic efficiency.

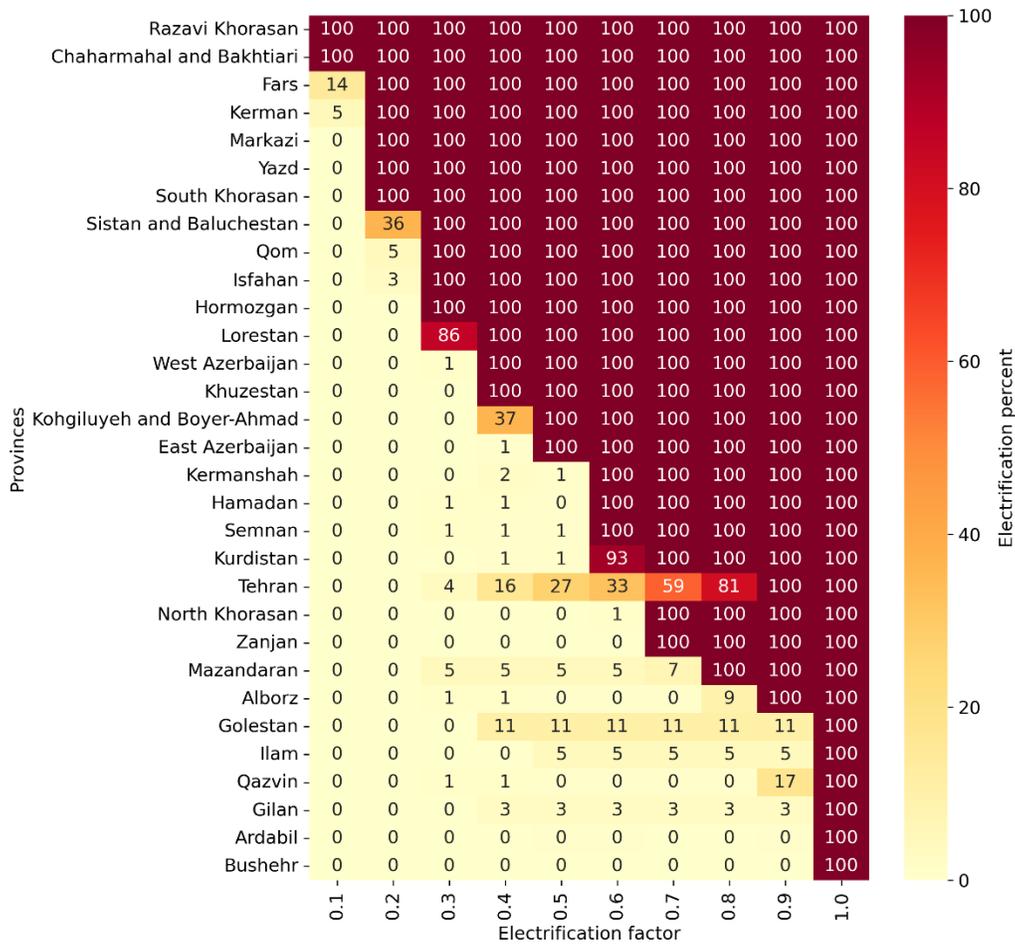


Fig. 15 Priority ranking of provincial heating demand electrification at different electrification levels.

Currently, gas-fired heaters dominate space heating in Iran, limiting the adoption of electric heating—potentially preventing it altogether. However, limited electrification may occur in gas-inaccessible or remote areas, such as parts of Sistan and Baluchestan. The figure below shows wind and solar deployment under varying heating electrification assumptions; for example, at 0% electrification, all heating demand is met by existing gas systems. Under these conditions, solar capacity remains at zero, and only 15,700 MW of wind power is deployed to meet cooling demand, sufficient to support up to ~4% heating electrification without additional renewable investment, reflecting a natural ceiling imposed by the dominance of gas-based systems.

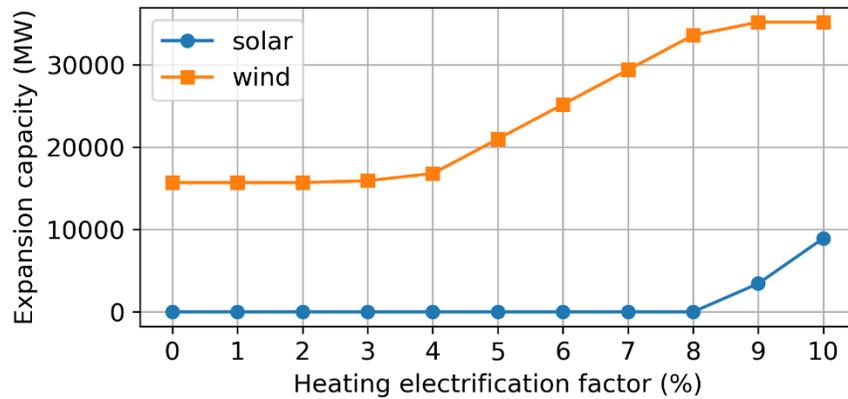


Fig. 16 Required wind and solar capacity expansion (MW) as a function of heating electrification factor (%)

As shown in Fig. 17, modeling assumptions critically shape outcomes. Case 1 (low temporal resolution) overestimates solar, ignoring storage — leading to max solar, zero wind/storage. Case 2 (high resolution) cuts solar by ~50%, shifts to wind in Razavi Khorasan, requiring costly transmission. Case 3 (endogenous co-optimization) reduces total cost by ~7% vs. Case 2, enhances robustness, and aligns renewables with high-potential, demand-proximate provinces (e.g., Razavi Khorasan, Chaharmahal & Bakhtiari), minimizing transmission. Storage scales with solar, highest in Case 3.

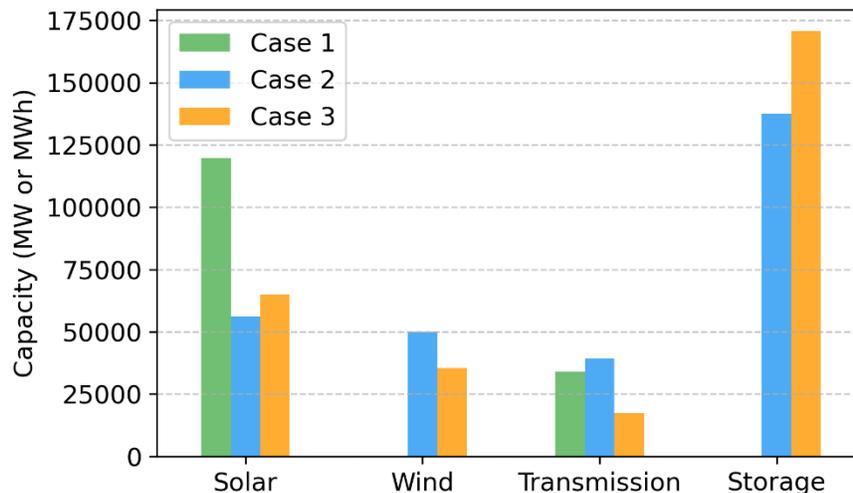


Fig. 17 Comparing total installation capacity of power generation, transmission and storage assets in different simulation cases.

Fig. 18 shows storage cost is the most influential parameter in both Cases 2 and 3. In Case 3, transmission parameters (cost, losses) have limited impact due to localized supply. Still, losses affect outcomes more than line costs, as higher losses raise generation/storage needs. Crucially, Case 3 exhibits lower sensitivity overall, confirming greater robustness from endogenous planning. categorizes the mentioned findings.

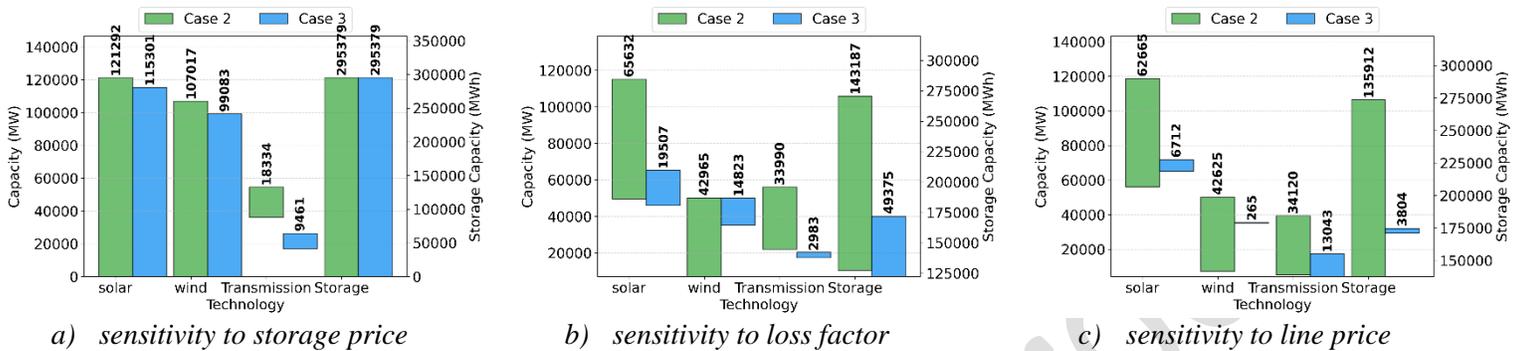


Fig. 18 Comparing the sensitivity of capacity expansion results to key parameters across simulation cases 2 and 3.

Table 4: Summary of key modeling findings

Category	Finding
Storage impact	High storage costs favor wind; low costs favor solar.
Regional potential	Solar needed widely; wind potential is regionally concentrated (e.g., Razavi Khorasan).
Electrification policy	Uniform provincial shares are suboptimal; endogenous allocation cuts costs by up to 7%.
Result robustness	Endogenous electrification yields more stable outcomes, less sensitive to grid cost/tech variations.
Temporal resolution	Coarse time modeling overestimates solar value and underestimates storage need.
Spatial alignment	Endogenous shares direct renewables to high-potential provinces near heating demand (e.g., Razavi Khorasan, Chaharmahal & Bakhtiari).
Heating electrification constraint	Gas heater dominance imposes a natural ceiling (~4%) on heating electrification; renewable expansion for cooling alone can support this level, but higher penetration requires substantial solar and wind deployment.

## 6- Conclusion

This study presents an optimization-based framework for planning renewable energy infrastructure to meet regional heating and cooling demands. By integrating building heat transfer equations and degree-day metrics, the model determines optimal renewable capacity, transmission needs, and storage specifications with computational efficiency. Application to a case study in Iran highlights solar PV as the primary technology due to its broad provincial potential, supported by battery storage to balance day–night fluctuations. Storage cost is identified as the most decisive factor: above \$150/kWh, wind becomes more competitive; at \$100–150/kWh, hybrid solar–wind portfolios are optimal; and below \$100/kWh, solar PV dominates with over 85% of generation.

Sensitivity results show that transmission costs and losses exert comparatively minor influence, especially when heating electrification shares are predetermined uniformly across provinces. However, when these shares are determined endogenously by the model, aligning electrification with local renewable potential

and demand proximity, total system costs are reduced by up to 7%. In such optimized cases, higher grid costs further discourage interregional transfers, promoting localized solar deployment even in moderate-resource areas to avoid expensive transmission from eastern wind hubs. Provinces such as Razavi Khorasan and Chaharmahal and Bakhtiari emerge as the most favorable options for electrifying heating systems, combining high renewable potential with proximity to demand centers.

While the model provides a robust planning tool, it does not account for the impact of heating/cooling system technologies on renewable selection, a limitation that points to valuable directions for future research.

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Uncorrected Proof