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Development of Iran's Electricity Transmission Capacity, Based on Forecasting the Demand Trend Using the System Dynamics Approach

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ABSTRACT

This research models and simulates the development of transmission capacity considering electricity supply and demand dynamics. After presenting a causal loop diagram and designing a stock and flow diagram, the model's validity is confirmed using validation methods for system dynamics models. The analysis then proceeds to scenarios for the total electricity demand in Iran. Firstly, the country's electricity demand structure is broken into industrial, household, agricultural, and other sectors. By studying consumption trends in each sector, linear and nonlinear regression are used to predict total electricity demand. Next, three scenarios - optimistic, moderate, and pessimistic - are defined in terms of electricity demand, and the required transmission capacity is calculated and designed for 400, 230, 132, and 63-66 kilovolt substations to cover and meet future electricity demand over twenty years. The research findings over a 20-year horizon indicate that in the moderate scenario, where electricity demand increases by 90 percent, the transmission capacity needs to increase by 106 percent to meet the demand. In the optimistic scenario, where electricity demand increases by 71 percent, the transmission capacity needs to increase by 85 percent. In the pessimistic scenario, where electricity demand increases by 110 percent, the transmission capacity needs to increase by 126 percent.

Keywords

System dynamics, Power transmission capacity, Expected power demand, Power transmission capacity development.

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1. Introduction

One of the most significant challenges and problems in the electricity industry that has led to its lack of development is related to reduced investment in the development of the transmission network and the aging of power transmission equipment (Rajabi Mashhadi, 2018). Due to high uncertainty regarding the amount, location, and timing of investments in the transmission sector (Kucuksayacigil and Min, 2021; Strbac et al., 2014), the power transmission system in Iran is constantly faced with challenges in timely investment development due to well-founded reasons, as reported by the Ministry of Energy and the current and past trends (Sha et al., 2018).

Transmission capacities with different ages and their losses, variable electricity demand and supply over time, and the relationship between required capacity and actual capacity, along with other intervening variables, contribute to increasing complexity and uncertainties in understanding the impact of these variables on each other. Additionally, the enforcement of sanctions in Iran has markedly heightened the intricacy of policy formulation in the electricity transmission sector.

Due to the significant impact of numerous parameters and variables in this field, the system dynamics have demonstrated their effectiveness in various economic and social issues and provide suitable capabilities. The prominent features of system dynamics compared to other methods that led to its employment in the current research are as follows:

- The ability to consider bilateral and feedback relationships between variables
- The ability to account for time delays between different variables, such as the delay between investment and capacity development
- The ability for computers to simulate and observe the behavior of key variables over time
- The ability to use the aging chain feature in simulations because the likelihood of capacity retirement is directly related to equipment age, which increases over time
- The ability to define scenarios and observe their effects on the future behavior of influential and key variables.

The primary focus of this study is to develop a model for electricity transmission capacity that incorporates different capacity expansion policies while also taking into account changes in demand. This research aims to address this issue by creating and validating a system dynamics model, designing projected demand scenarios based on historical consumption data from industrial, household, agricultural, and other sectors, and then estimating sustainable transmission capacity growth within the Iranian power grid over the next two decades.

2. Literature review

Long-term planning in expanding the power transmission network provides a systematic and profitable expansion of electrical equipment and facilities to meet the expected energy demand with a reliable degree of certainty (Ude et al., 2019). Researchers have made efforts to propose a scheme to encourage investment in the transmission sector (Contreras et al., 2009). In a study, the impact of tariff policies on the cash flow of the power grid was examined, and an optimization decision-making model for investment was developed (He et al., 2018). Researchers have used system dynamics to model the relationship between investment and electricity transmission capacity, showing that transmission capacity planning can be centralized or decentralized, each having its advantages and disadvantages. Additionally, researchers have simulated the power transmission industry of Colombia using their model (Zambrano et al., 2019).

Furthermore, past studies have shown that most electricity structure analyses have been predominantly focused on the production sector(Dismukes et al., 1998), and the use of system dynamics in this sector of the electricity industry has been inevitable (Dehghan et al., 2021; Monjazeb and Rezaei Movahed, 2019; Sha et al., 2018; Shiu et al., 2023). System dynamics has shown that besides investing in production equipment, investments in research and development (R&D) and efficiency are also crucial. Demand management strategies and reduction, such as increasing the efficiency of consumer equipment, play a prominent role in demand and production sustainability (Qudrat-Ullah, 2013).

With research in Iran, a model for developing the supply sector in the electricity industry considering all technical, technological, economic, and environmental dimensions has been presented. By utilizing this model, a long-term plan for extracting electrical energy supply can be developed. A comparison between the current development trend and a model-based development trend shows that using a system dynamics-based model can lead to economic savings in electricity development (Mohaghar and Najafzadeh, 2017). Another domestic study has proposed a model for investment in developing power distribution capacity. This research suggests a combined method incorporating centralized and decentralized development features. This planning method improves the timing of investments compared to decentralized methods while reducing consumption costs compared to centralized methods (Ahmadvand and Kalantari Hermzi, 2019).

Another factor intensifying the need for increased investment in the electricity industry is related to losses. In Iran, using data from 1383 to 1393, losses have been predicted using both system dynamics and regression statistical methods, showing that econometric methods provide more accurate estimates than system dynamics models. System dynamics models are more suitable for demonstrating cause-and-effect relationships between variables and the extent of each variable's impact on another. Another study has reviewed the application of system dynamics in the electricity industry (Ahmad et al., 2016).

Also, the utilization of statistical methods and deep learning has been extensively employed in previous research to forecast electricity consumption (Mateo-Barcos et al., 2024; Qureshi et al., 2024; Rao et al., 2023; Meira et al., 2023), and as accurate long-term electricity demand predictions are essential for the investment and operation of future energy systems (Grandon et al., 2024), this study employs regression methods to forecast Iran's electricity consumption and design demand side scenarios.

Table 1 summarizes previous system dynamics research results and highlights their differences compared to the current study.

Table 1. Comparison of past systems dynamics studies and current research

Row	Study	Country	Sector			Study focus
1	(Ford, 2001)	USA	*			Use of computer models for power plant simulation
2	(Nahavandi and Najafzadeh, 2012)	Iran	*		*	Comparison of two supply-side development approaches in demand management
3	(Qudrat-Ullah, 2013)	Canada	*		*	Investment in research and development (R&D)
4	(Pereira and Saraiva, 2013)	Spain	*			Long-term model for the generation expansion planning problem
5	(Mohaghar and Najafzadeh, 2017)	Iran	*			Long-term program development for electricity supply
6	(He et al., 2018)	China		*		Impact of Transmission and distribution tariff policies on electricity industry cash flow
7	(Sha et al., 2018)	China		*	*	Capital allocation strategy in the transmission and distribution sector
8	(Sha et al., 2018a)	China		*		Impact of transmission and distribution tariffs on capital investment allocation in the power grid
9	(Ahmadvand and Kalantari Hermzi, 2019)	Iran			*	Investment in distribution capacity development
10	(Monjazeb and Rezaei Movahed, 2019)	Iran		*		Transmission Losses
11	(Zambrano et al., 2019)	Colombia		*		Investment in transmission capacity, installed transmission capacity, current marginal cost, Transmission capacity marginal cost, desired transmission capacity marginal cost, electricity demand
12	(Saad et al., 2020)	Malaysia	*			Evaluation of tariff rate changes and their effects on production
13	(Dehghan et al., 2021)	Iran	*		*	Impact of energy price policies on supply and demand instability
14	(Dianat et al., 2021)	Iran	*			Systematic modeling of power generation development planning
15	(Li et al., 2022)	China			*	Electricity consumption forecasting using system dynamics tools

Row	Study	Country	Sector			Study focus
16	(Zahari and Mclelan, 2023)	Indonesia	*			Using a conceptual dynamic model to understand the electricity sector energy transition to renewables
17	(Loh and Bellam, 2024)	Singapore	*			Effect of government policies on hydrogen energy, low carbon electricity imports, and energy saving on energy security
Current study		Iran		*		Investigation of capacity development in power grid transmission to ensure sustainable electricity supply under different demand scenarios, considering variables such as losses, inflation, aging chain, and equipment depreciation.

Knowing that none of the mentioned researchers have specifically modeled the development of electricity transmission capacity based on different demand scenarios, this research, utilizing system dynamics tools, and focuses on predicting and simulating the construction of transmission capacity separately for 400, 230, 132, and 66-63 voltage levels based on expected demand scenarios under different conditions.

3. Research methodology

3.1. System dynamics

Figure 1 presents the steps of the system dynamics methodology (Sterman, 2002).

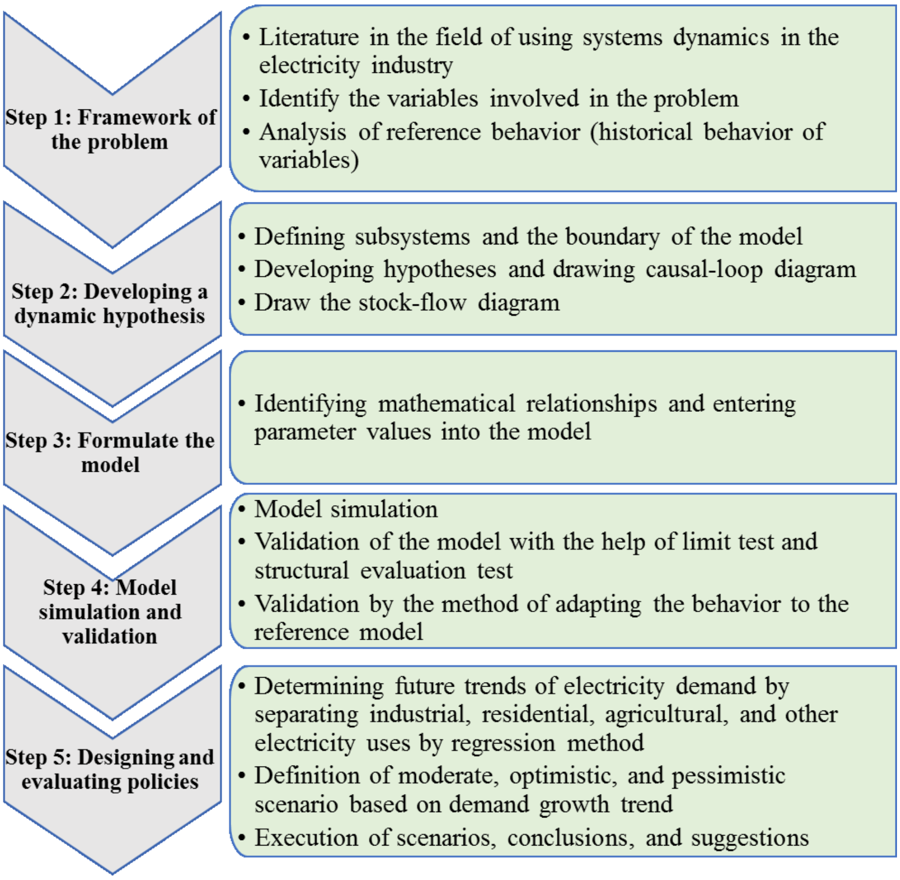


Figure 1. Research methodology (Sterman, 2002)

The explanation of Figure 1 is as follows:

Step 1- Problem Framework: This step is a meticulous process where the research problem is defined with precision. A thorough understanding of the problem is gained, and the approximate and deep structure of the research model is identified through a comprehensive study of existing sources and the valuable insights of stakeholders.

Step 2- Formulation of dynamic hypothesis: Dynamic hypotheses are extracted after identifying the subsystems, variables, and feedback loops present in each subsystem, and studying the behavior of variables in the past. In this stage, the causal loop diagram of the system is created using the identified variables and loops. The proposed causal loop diagram consists of three balancing loops and two reinforcing loops. Additionally, after identifying stock and flow variables, a stock and flow diagram is drawn.

Step 3- Formulating the Model: This step is a comprehensive process where the mathematical relationships between variables are determined, ensuring a deep understanding of the system's dynamics.Step 4- Simulation and Validation: In this step, the mathematical model is simulated using software designed for simulating systemic models. In this paper, Vensim PLE software has been used. In order to ensure that the model accurately represents the system's realities, validation is conducted. In order to validate the model, data from Iran's electricity industry from 1360 to 1400 were used, and the model was simulated using time steps of 0.015. Validation includes tests such as behavioral reproduction test, structural test, structural behavioral test, extreme condition test, and dimensional consistency.

Step 5- Designing and Evaluating Policies: In this step, to test strategies, the impact of these strategies is quantified using the model. In this article, scenarios were defined using regression analysis tools and based on Iran's electricity demand trend from 1350 to 1400. In the moderate scenario, it was assumed that the non-linear trend of Iran's electricity demand increase would continue similarly to before over a 20-year horizon. In the optimistic and pessimistic scenarios, it was assumed that electricity demand would be 10% lower and higher than the demand trend in the moderate scenario, respectively.

3.2. Choose of variables

The common voltage levels for power transmission capacity in the Iran power transmission system are 400 kV and 230 kV, and for sub-transmission, they are 132 kV and 63-66 kV. In this article, based on the classification presented in specialized reports, the aging chains of transmission equipment have been categorized into equipment with a lifespan of less than 30 years, between 30 and 50 years, and over 50 years (Rajabi Mashhadi, 2018).

The key variables used in the modeling, along with their type, unit, and source, are presented in Table 2.

Table 2. Key Variables Defined in the Model

Row	Variable name	Type	Unit	Reference
1	Transmission capacity depreciation	Endogenous	$\frac{MVA}{Year}$	(Ahmad et al. 2016; He et al. 2018)
2	Transmission capacity development	Endogenous	$\frac{MVA}{Year}$	(Ahmad et al. 2016; Zambrano et al. 2019)
3	Transmission capacity with 30-50 years old	Endogenous	MVA	(Romero-Quete et al. 2016)
4	Transmission capacity with <30 years old	Endogenous	MVA	(Romero-Quete et al. 2016)
5	Transmission capacity with >50 years old	Endogenous	MVA	(Romero-Quete et al. 2016)
6	Transmission capacity	Endogenous	MVA	(Romero-Quete et al. 2016; Zambrano et al. 2019)
7	Transmission line development	Endogenous	$\frac{CK}{Year}$	Electrical industry experts
8	Transmission line	Endogenous	CK	Electrical industry experts
9	Cost of replacing	Endogenous	BRial	Electrical industry experts
10	Depreciated capacity replacing	Endogenous	$\frac{MVA}{Year}$	(He et al. 2018)
11	Investment in transmission capacity development	Endogenous	$\frac{BRial}{Year}$	(Zambrano et al. 2019)
12	Unit cost of transmission capacity development	Endogenous	$\frac{BRial}{MVA}$	Electrical industry experts
13	Desired transmission capacity	Endogenous	MVA	Electrical industry experts
14	Desired investment in transmission capacity development	Endogenous	$\frac{MVA}{Year}$	Electrical industry experts
15	Desired transmission losses	Endogenous	$\frac{1}{Year}$	(Pourkashani and Babaei 2003)
16	Desired vs current losses	Endogenous	$\frac{1}{Year}$	(Pourkashani and Babaei 2003)
17	Electricity demand	Exogenous	MW	(Dehghan et al. 2021)
18	Hazard function	Exogenous	DMNL	(Pe 2003)
19	Total capacity of the power plants	Endogenous	MW	(Dehghan et al. 2021)
20	Total transmission capacity	Endogenous	MVA	Electrical industry experts
21	Transmission losses	Endogenous	$\frac{1}{Year}$	(Pourkashani and Babaei 2003)
22	Unit cost of capacity development	Exogenous	$\frac{BRial}{MVA}$	Electrical industry experts

4. Dynamic hypothesis

The feedback loops considered in this research are three balancing loops and two reinforcing loops. The two balancing loops in the model are related to the lifespan of transmission equipment. Balancing loop B1 in Figure2 indicates the possibility of sudden burning due to increased transformer lifespan based on the Hazard distribution function (Pe, 2003).

Additionally, in balancing loop B2, transmission equipment is consumed due to increased lifespan and losses (He et al., 2018).

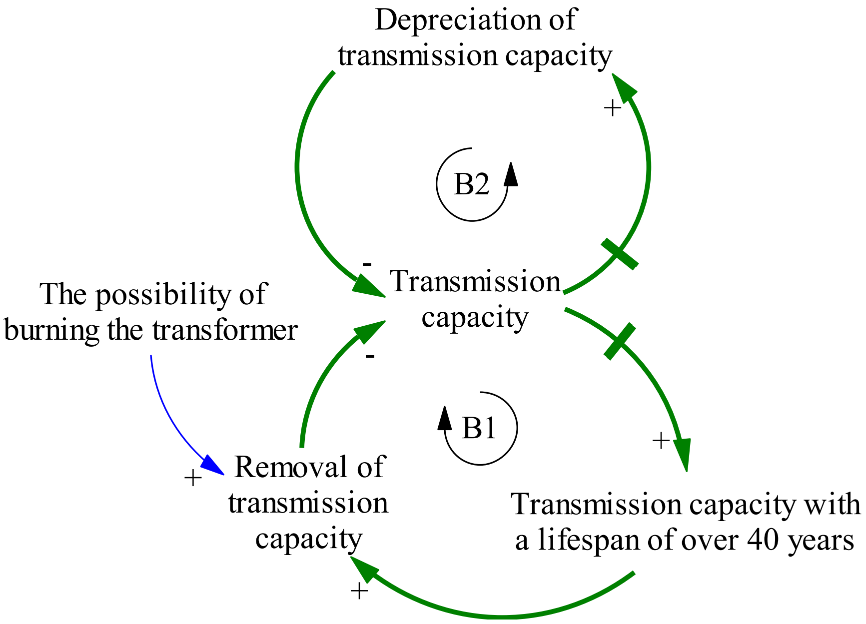


Figure 2. Two balancing loop impact on transmission capacity

The Hazard distribution function is based on Figure 3. In this diagram, as the lifespan of transformers increases, the probability of their burning with an S-shaped behavior increases.

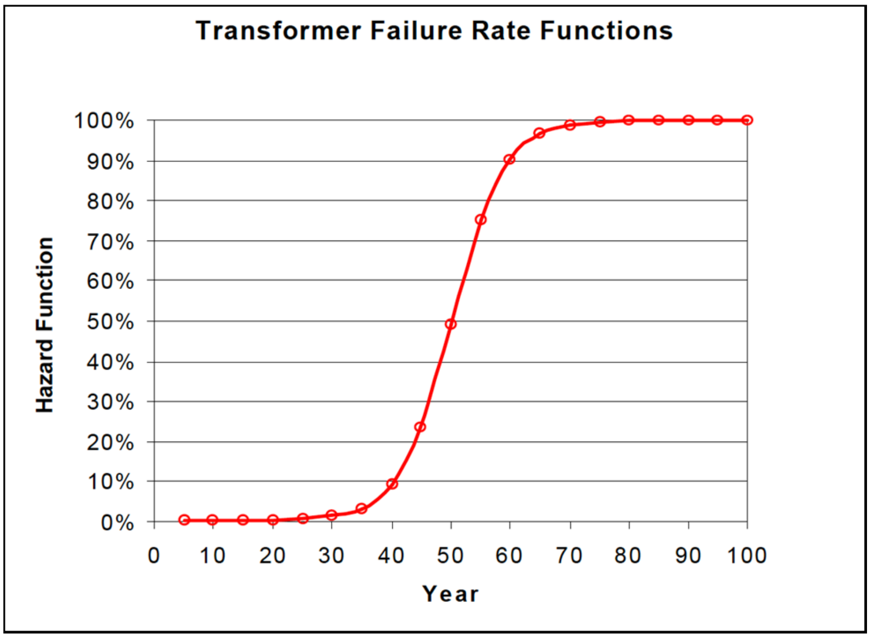


Figure 3. Hazard distribution function (PE, 2003)

In balancing loop B3 presented in Figure 4, with a decrease in transmission capacity, the difference between expected capacity and actual capacity increases, and investment also increases (Zambrano et al., 2019). With delayed investment, transmission capacity develops, leading to increased capacity. Therefore, the decrease in transmission capacity will ultimately be compensated over time through this loop.

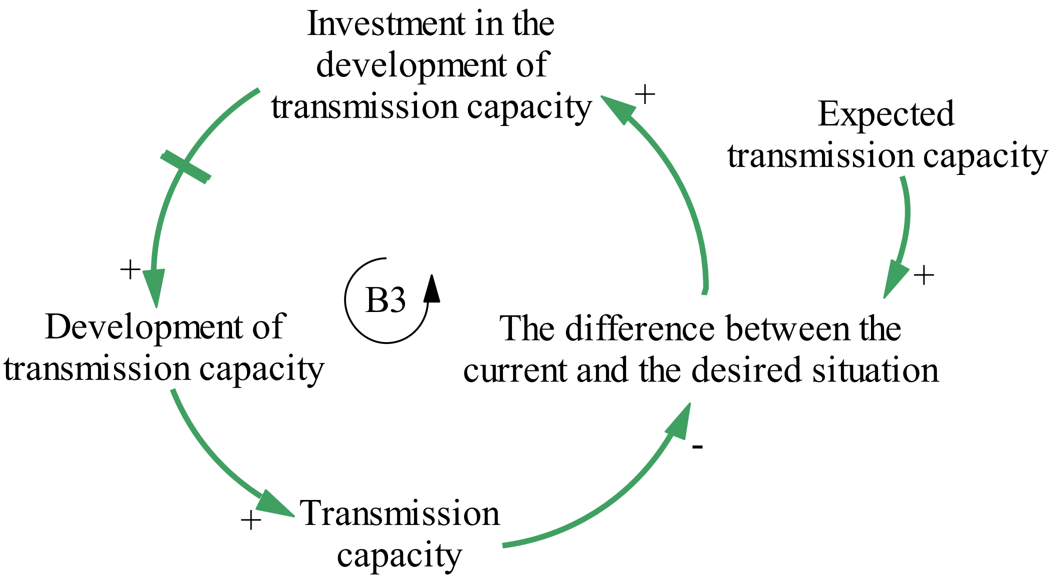


Figure 4. Third balancing loop impact on transmission capacity

The efficiency of the transmission network is defined as the ratio of network output power to its input power, and network losses are calculated by subtracting efficiency from 1. The reinforcing loop in Figure 5. illustrates the impact of transmission network losses on capacity development. This long-term influential loop shows that as investment in capacity development increases, capacity development expands and capacity increases. However, in the long term, the lifespan of the transmission network increases, and network losses also increase (Rajabi Mashhadi, 2018), necessitating more capacity to compensate for losses, ultimately leading to increased investment in capacity development. Given the qualitative essence of political factors in the system, such as the imposition of sanctions, inflation serves as a quantitative indicator of the influence of these factors on the development of the electricity transmission system. This exogenous variable elevates the unit costs associated with capacity expansion, subsequently impeding the pace of capacity development.

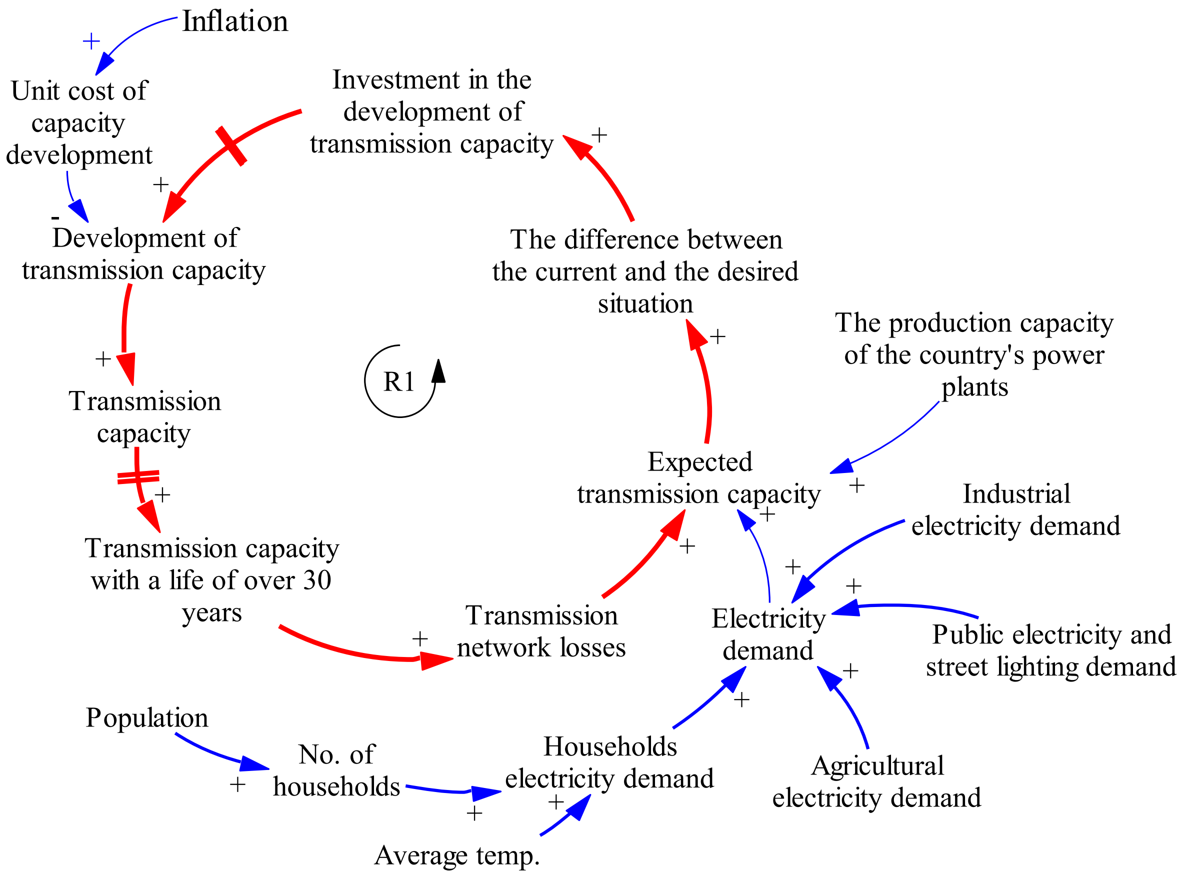


Figure 5. First Increasing Loop Impact on Transmission Capacity

In Figure 6, the country's electricity demand includes demand for household, agricultural, industrial, public, and street lighting electricity. In 1400, according to Figure 6, the industrial, household, and agricultural sectors accounted for 39%, 35%, and 15% of electricity consumption, respectively, and are among the major electricity consumers. The scenarios defined in the model are based on the relationships presented regarding electricity demand.

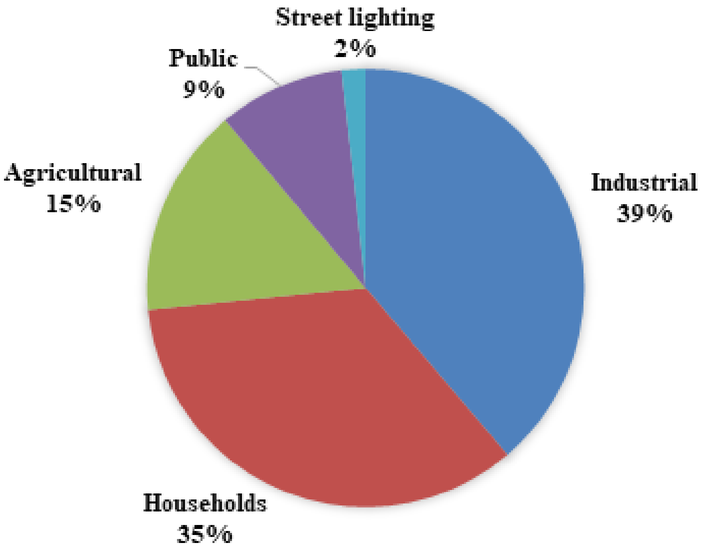


Figure 6. Share of electricity consumption users in 1400 (Tavanir, 2022)

Figure 7 shows the amount of power in the transmission network that has a lifespan of over 30 years. As evident, from 1376 onwards, the lifespan of the power transmission network has reached 30 years, leading to an increase in losses caused by this equipment.

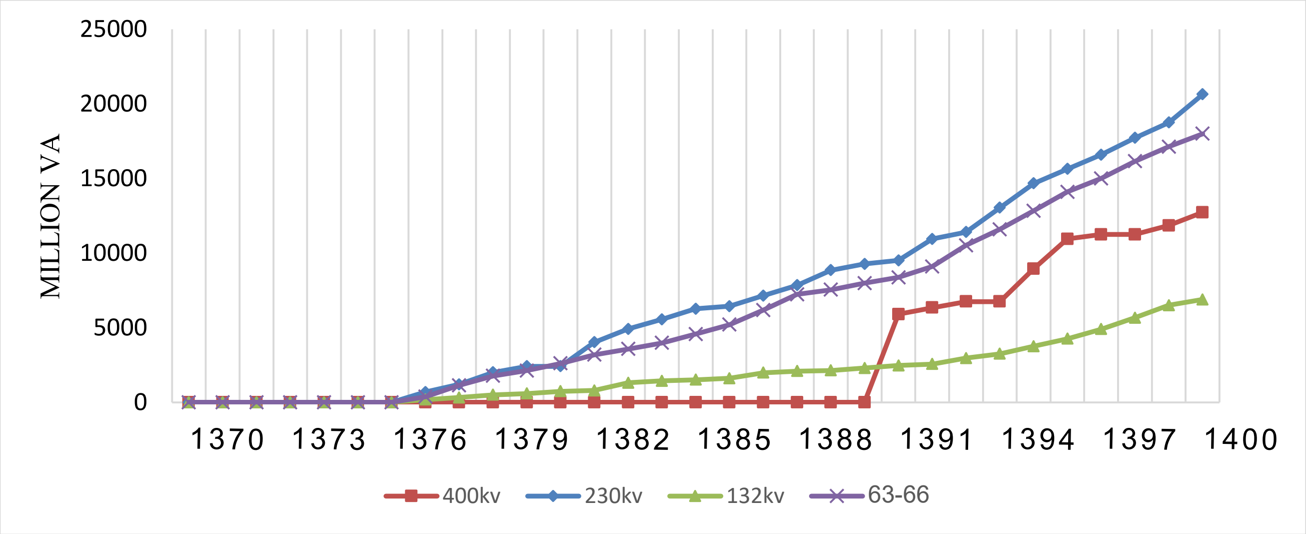


Figure 7. Transmission network power capacity over 30 years separated by transformer type (Tavanir, 2022)

Figure 8 also illustrates the second reinforcing loop, showing the impact of network losses and expected losses on strategies in capacity development. As the developed capacity increases, the lifespan of these equipment increases in the long term, leading to an increase in their losses (Rajabi Mashhadi, 2018; Romero-Quete et al., 2016). The difference between actual losses and targeted losses in strategies increases the decision to renovate and invest in new capacity development, resulting in increased transmission capacity.

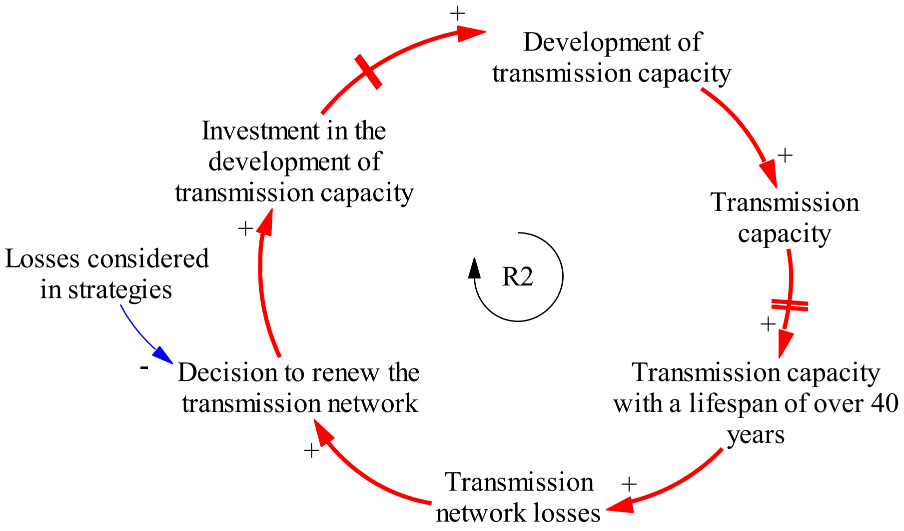


Figure 8. Second reinforcing loop impact on transmission capacity

By joining all the loops explained above, Figure 9 creates an overall causal loop diagram of the research.

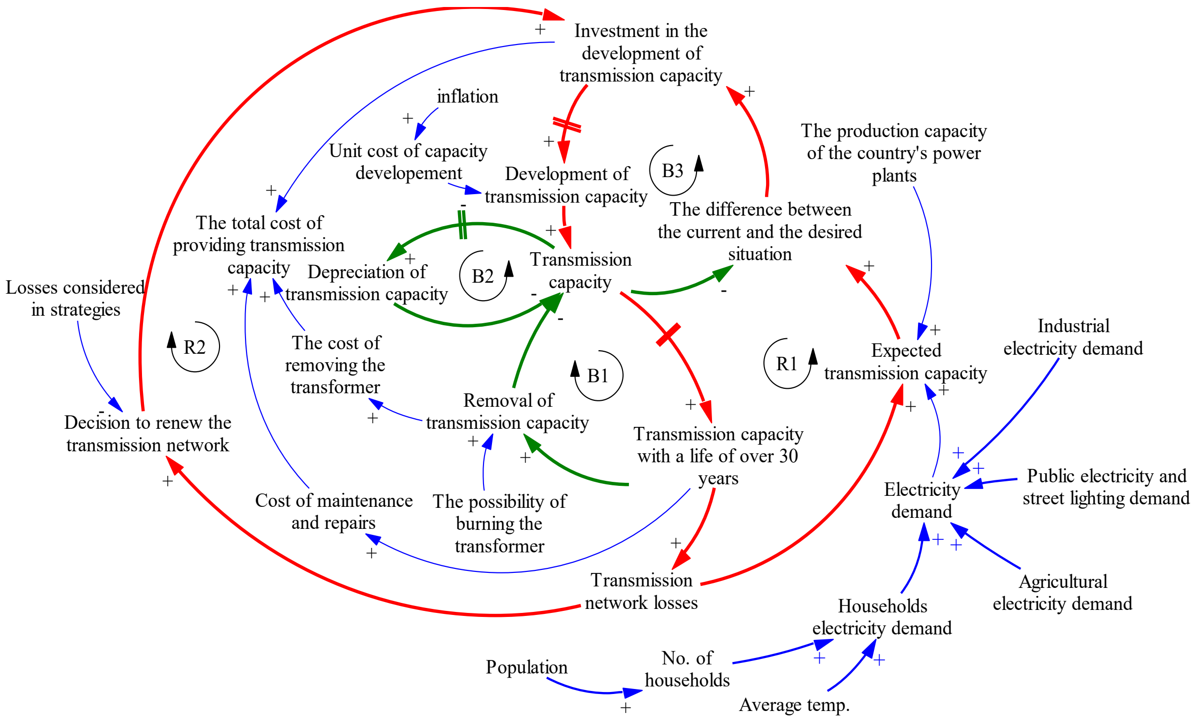


Figure 9. Overall Causal loop diagram of the Research

5. Stock and flow diagram

Considering variables such as transformer capacity, transmission line length, and Consumer Price Index (CPI) as stock variables, the stock and flow diagram presented in Figure 10 and Figure 11 has been developed. After drawing the stock and flow diagram, it is necessary to define the mathematical relationships between variables. The mathematical relationship between the amount of post-capacity development based on first-order information delay is considered. Equation 1 shows the relationship between the amount of investment and the amount of developed capacity. In this equation, D_K represents the amount of development for each capacity, I_K is the amount of investment made in each capacity, and U_K represents the unit cost of developing each capacity. In equation 1, Delay1i function represents first-order information delay.

$$D_K = Delay1i\,(\frac{I_K}{U_K},1,0) \tag{1}$$

$$K\epsilon\ 400KV, 230KV, 132KV\ and\ 63-66KV\ transmission\ capacity$$

It is worth mentioning that the amount of investment in the field of transmission capacity expansion is also calculated based on the expected transmission capacity (DTC) and expected losses (DTL). In Equation 2, TC represents the current amount of transmission capacity, and TL represents the current amount of losses.

$$I_K = U_K \times max(0, DTC - TC) \times (1 + DTL - TL) \tag{2}$$

The parameter determining the amount of transmission losses is the average age of all transmission capacity, calculated by Equation 3. In this equation, TC_i represents the amount of transmission capacity with an age of i years, and A represents the average age of the transmission network.

$$A = \frac{\sum_i i \times TC_i}{\sum_i i} = \frac{1 \times TC_1 + 2 \times TC_2 + \cdots + TC_{100}}{1 + 2 + 3 + \cdots + 100} \tag{3}$$

To calculate the amount of transmission network losses, a Lookup table function has been used. According to Equation 4, the amount of network losses is a function of the average age of the transmission network (A), and for each value of A, the network losses are calculated using interpolation.

$$Tl = F\ (A) \tag{4}$$

For better presentation, the aging chain section of transmission capacities designed separately for the four mentioned capacities is presented in the stock and flow diagram. Figure 10 shows variables affecting transmission capacity. In this diagram, the amount of investment in capacity development and unit cost of capacity development enter the aging chain section, and the amount of transmission capacity is separated by four capacities exiting from this section. The model related to transmission capacities is also shown in Figure 11.

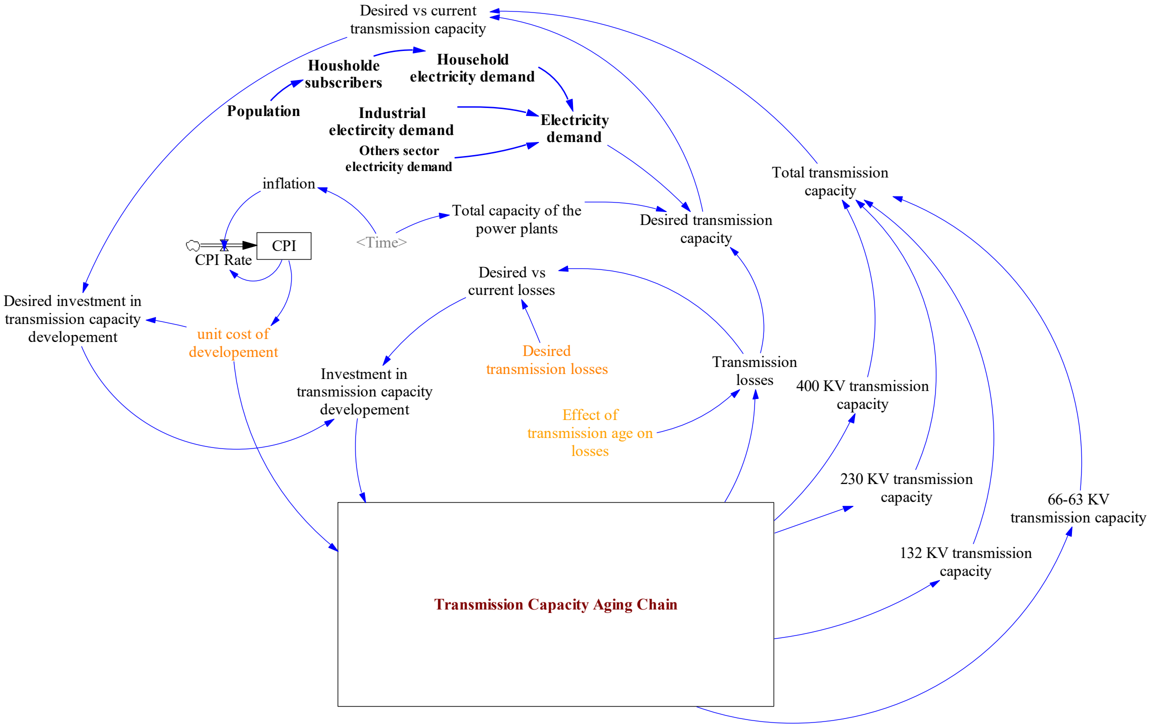


Figure 10. Stock and flow diagram containing variables affecting transmission capacity

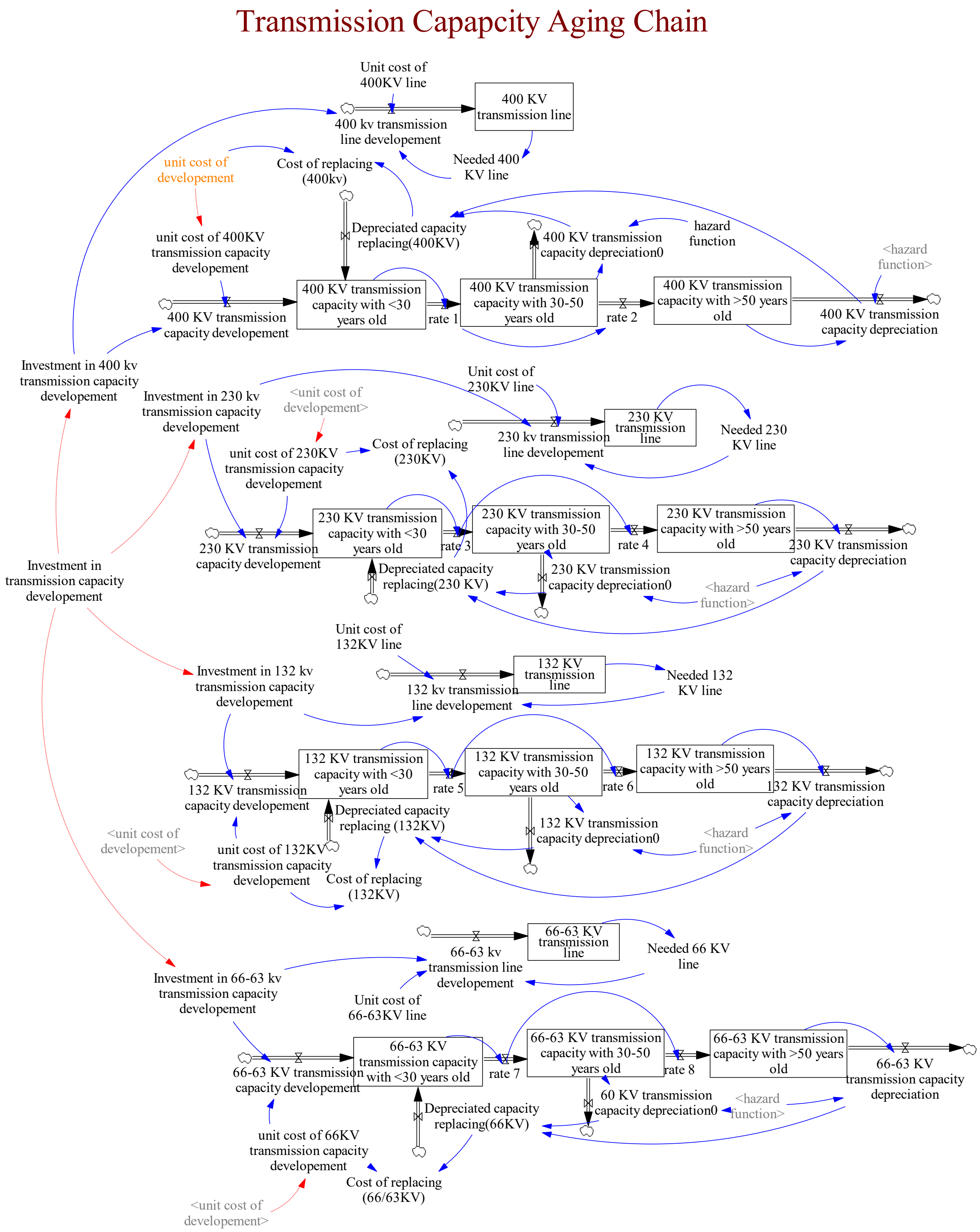
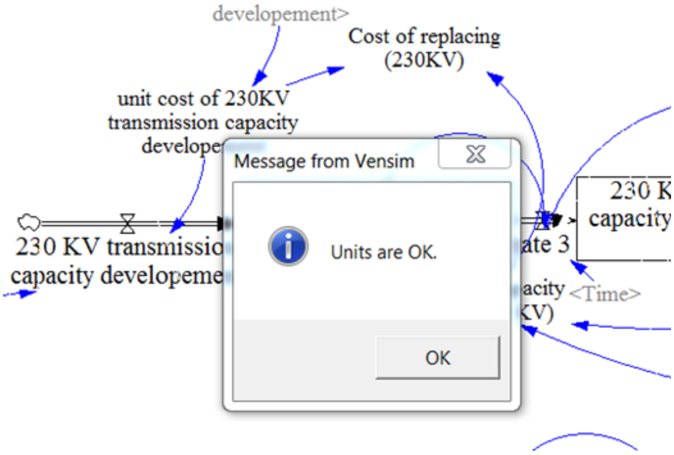


Figure 11. Stock and flow diagram of aging chain part in transmission capacity

6. Model validation

In this section, after simulating the model, its validation has been carried out. In this research, model validation has been confirmed using various methods such as structural evaluation, extreme condition testing, dimensional consistency, and behavioral reproduction tests (Sterman, 2002).

Here, only the presentation of results from dimensional consistency and behavioral reproduction testing are provided. Figure 12 displays the compatibility results of the model dimensions, which were performed using the Vensim software.



Message from Vensim

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Figure 12. Dimensional consistency results in Vensim PLE software

In behavioral reproduction testing, the simulation results of the model are compared with available historical data for key variables. The current research model was able to accurately simulate the behavior of transmission capacity variables. Figure 13 shows the results of the simulation and historical data for the 400 KV transmission capacity variable. As observed, the model was able to reconstruct the behavior of this variable with an accuracy exceeding 90%. Also, Figure 14, Figure 15, and Figure 16 show the results of the behavioral reproduction test for 230, 132, and 63-66 kilovolt transmission capacity, respectively.

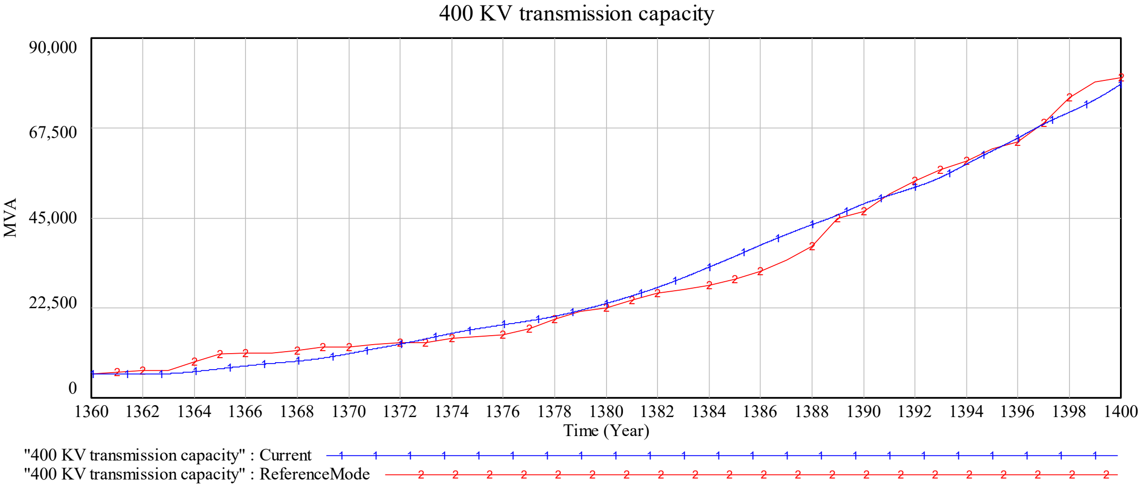


Figure 13. Comparison of historical data and simulation result of 400 KV transmission capacity (MAE: 6.9%)

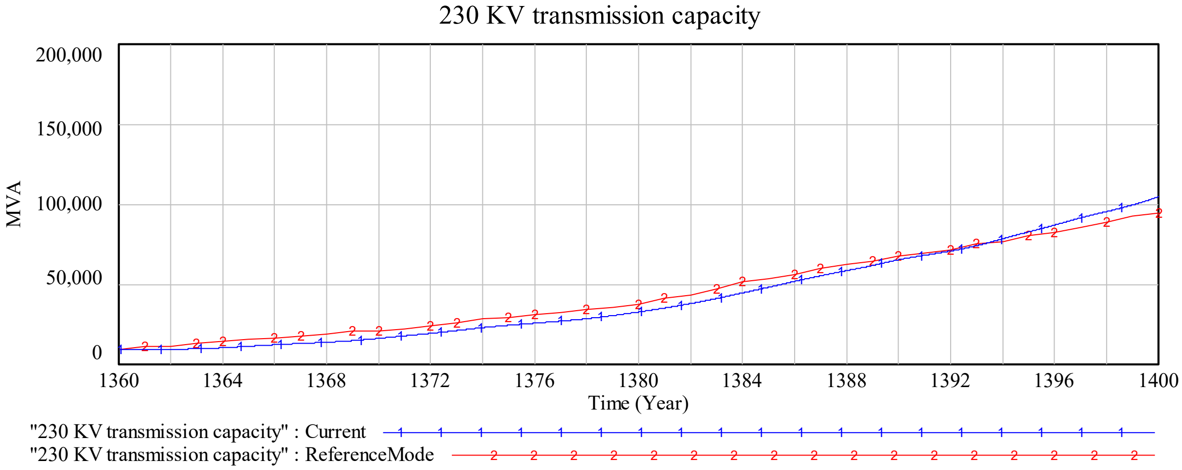


Figure 14. Comparison of historical data and simulation result of 230 KV transmission capacity (MAE: 9.9%)

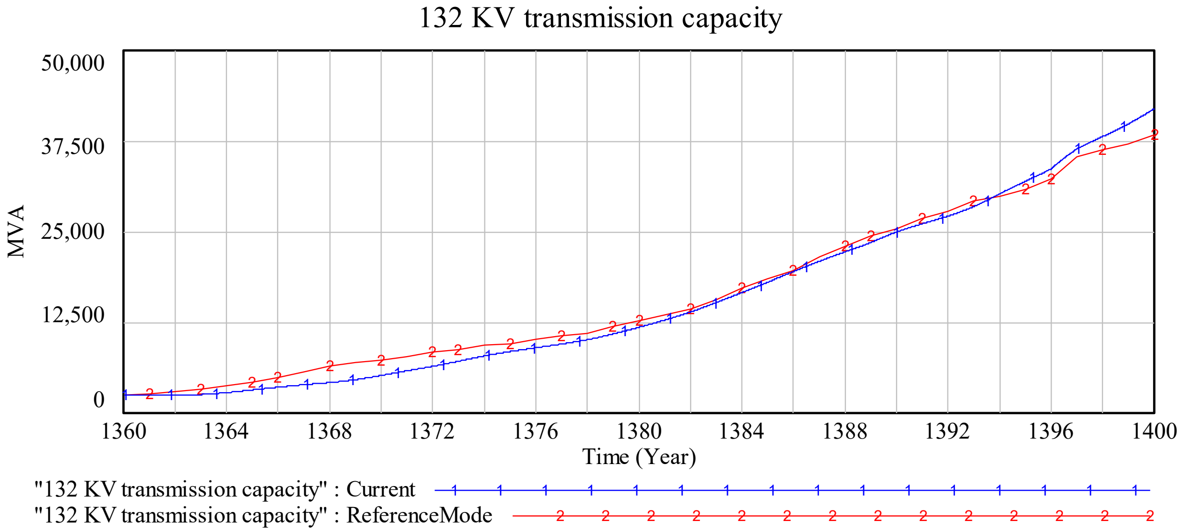


Figure 15. Comparison of historical data and simulation result of 132 KV transmission capacity (MAE: 6.9%)

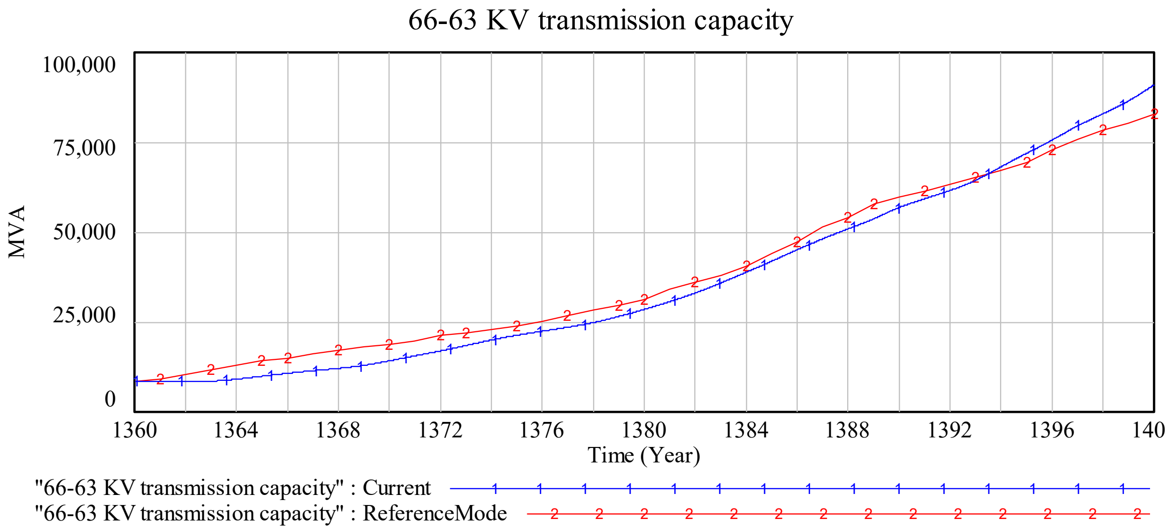


Figure 16. Comparison of historical data and simulation result of 63-66 KV transmission capacity (MAE: 8.4%)

7. Future analysis of the electricity transmission industry

In this section, the expected trend has been predicted based on the major electricity consumers identified in Figure 6 to investigate the impact of electricity demand on the level of transmission capacity development. Regarding the industrial sector, the consumption trend over time is shown in Figure 17.

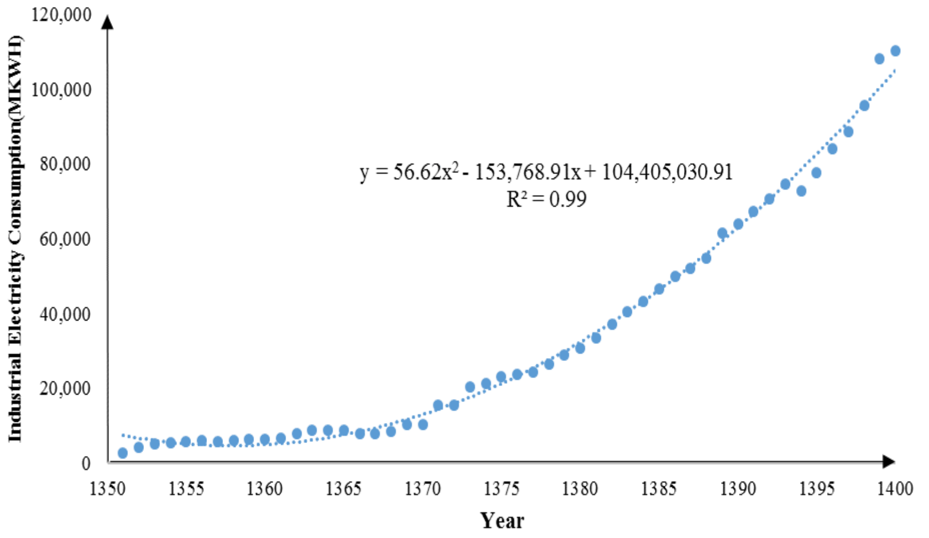


Figure 17. Industrial electricity consumption trend in Iran

Equation 5 shows the best relationship that can predict electricity consumption in the industrial sector based on the Persian year as follows.

$$ID = 56.45 \times Y^2 - 153312 \times Y + 104091642 \quad (5)$$

In the residential sector, Figure 18 shows the number of household subscribers based on the population from 1346 to 1400. The relationship between the increase in the number of household subscribers and the country's population is not linear, and the slope of its increase has gradually increased over time. The reason for this is the decrease in household size at the national level. Equation 6 shows the best function that can represent the relationship between the number of household subscribers (HS) based on the population (P).

$$\mathrm{HS} = 0.0076 \times P^2 - 0.3887 \times P + 6.4377 \tag{6}$$

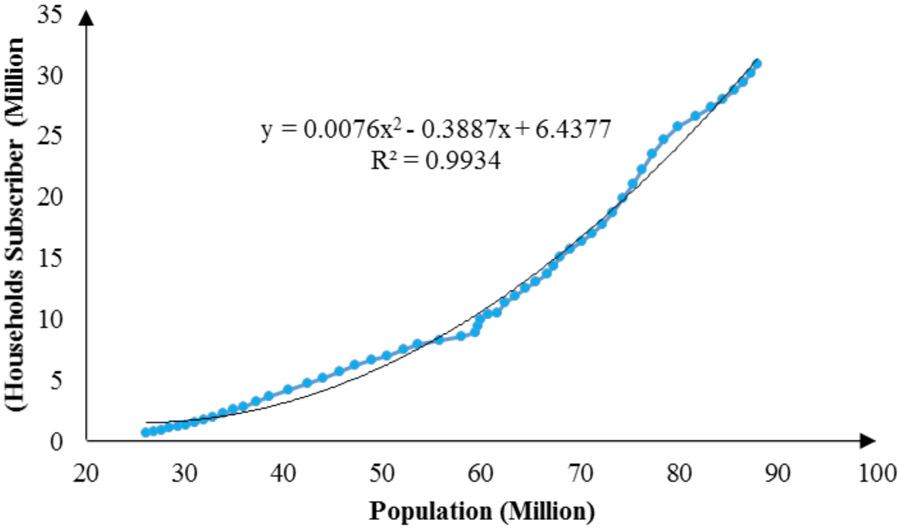


Figure 18. Household subscriber numbers based on population

In order to examine the relationship between household electricity demand and the number of subscribers in this sector, the correlation between demand and the product of subscribers and average air temperature was investigated (Figure 19). The best relationship that can represent the relationship between electricity demand and the product of subscribers and air temperature is a nonlinear relationship presented in Equation 7.

$$HD = 157.13 \times T \times HS - 5346.5 \tag{7}$$

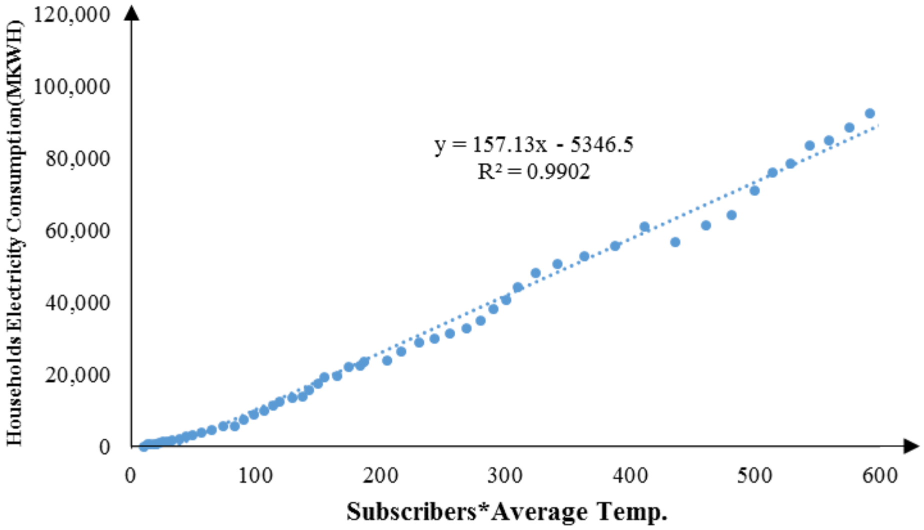


Figure 19. Household electricity demand based on the number of subscribers and average temperature

Figure 20 shows the agricultural electricity consumption trend over time. Equation 8 presents the best relationship for modeling electricity consumption (AD) over time in the agricultural sector.

$$AD = 29.97 \times (Y)^2 - 81587.15 \times (Y) + 55522451.95 \tag{8}$$

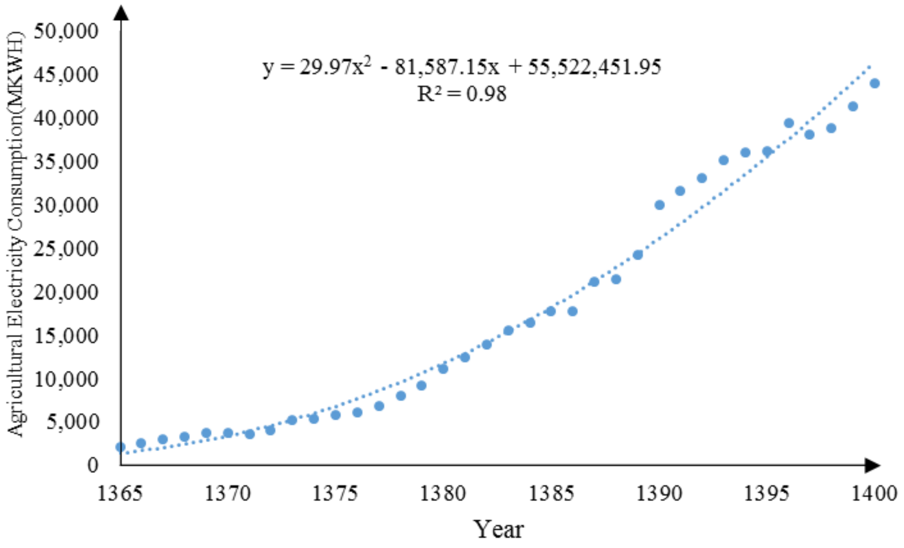


Figure 20. Agricultural electricity consumption trend over time

Other electricity demands (OD) in the country are related to public and street lighting consumption. The relationship of increasing demand in this sector is also in accordance with the equation presented in Figure 21, which increases linearly over time (Equation 9).

$$OD = 2136.99 \times (Y) - 2937529.95 \tag{9}$$

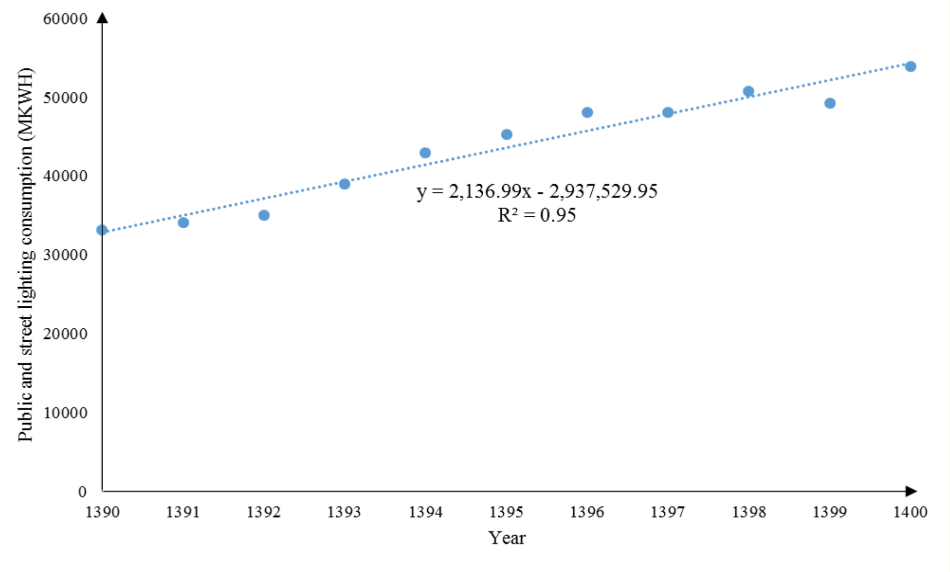


Figure 21. Public electricity consumption and street lighting trend

7.2. Scenario 1: Continuation of electricity demand trend until 1420 (moderate scenario)

In scenario one, it is assumed that the country's electricity demand, which is formulated based on the causal relationships in Figure 22, will increase according to equations 5 to 9. This increase occurs under conditions where the air temperature remains at the same level as the average temperature of 1400, which is 19 degrees Celsius, and the country's population increases linearly to reach 108 million by 1420.

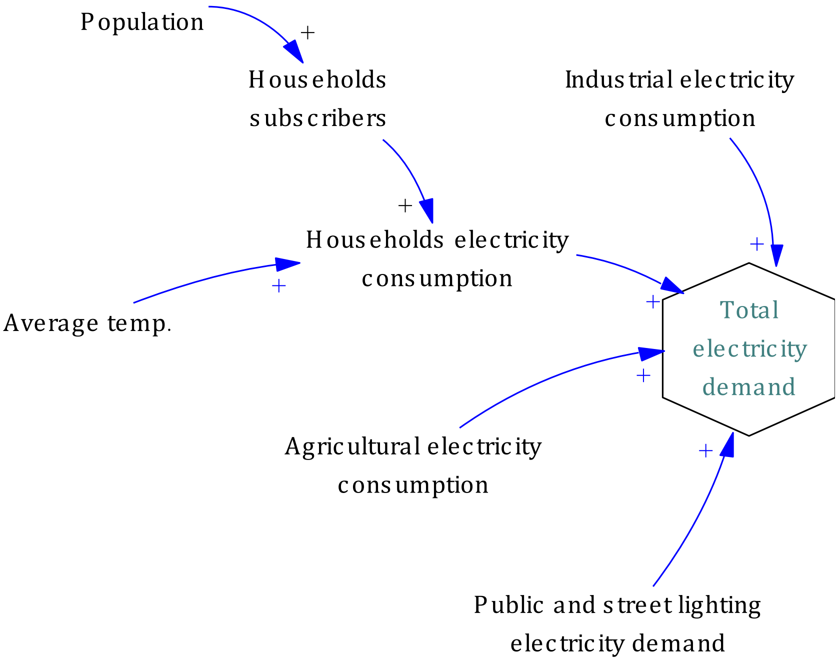


Figure 22. Causal relationships indicating the country's electricity demand

Under these conditions, the behavior of Iran's total electricity demand will be as shown in Figure 23.

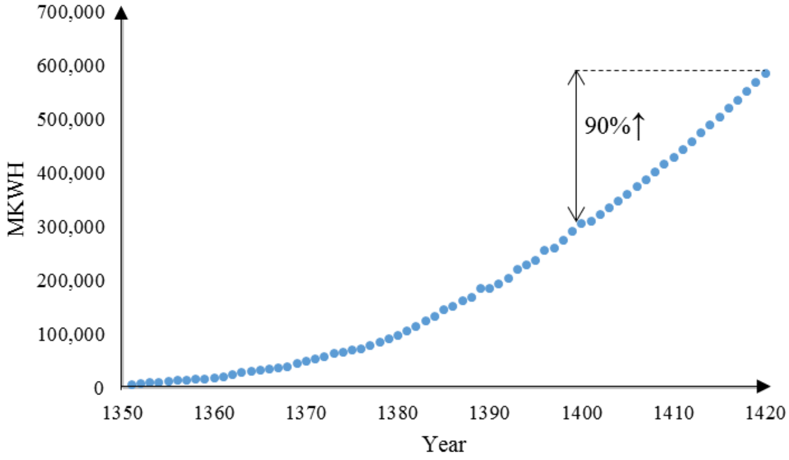


Figure 23. The trend of Iran's electricity demand until 1420 in scenario 1

In this scenario, which is considered the most likely scenario, the prediction provided regarding the country's electricity demand has been integrated into the model. According to Figure 24, the amount of transmission capacity increases to compensate for demand.

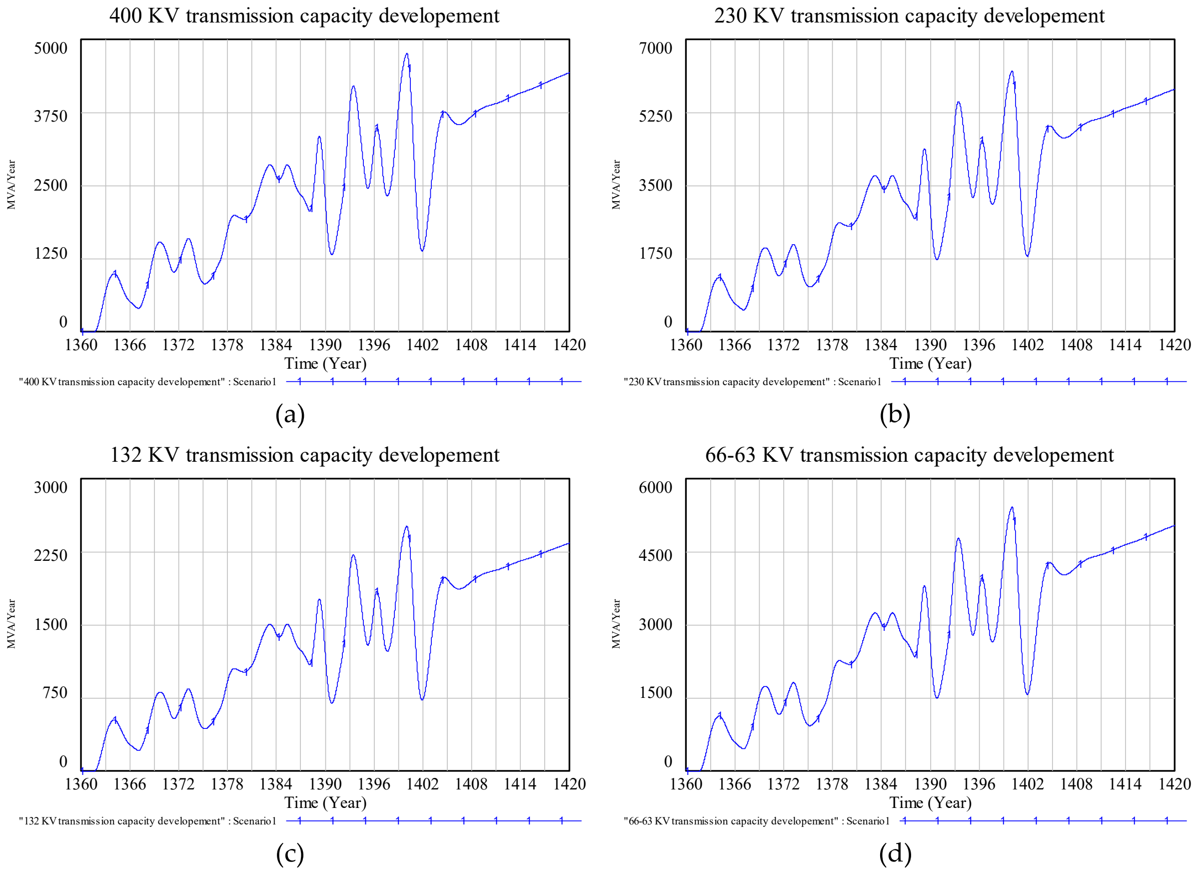


Figure 24. Transmission capacity behavior by scenario 1: (a) 400 KV; (b) 230 KV; (c) 132 KV; (d) 63-66 KV

The outcomes of simulating the scenario of maintaining the existing conditions (moderate scenario), as the numerical results depicted in Table 3, indicate that an expansion of 89%, 112%, 115%, and 110% in the transmission capacities of 400, 230, 132, and 63-66 KV in the 20-year horizon is required to meet the current electricity demand within the network.

7.3. Scenario 2: Increases in electricity demand until 1420 (pessimistic scenario)

In this scenario, the country's electricity demand is assumed always to be 10% higher than the prediction provided in scenario 1 (Figure 25).

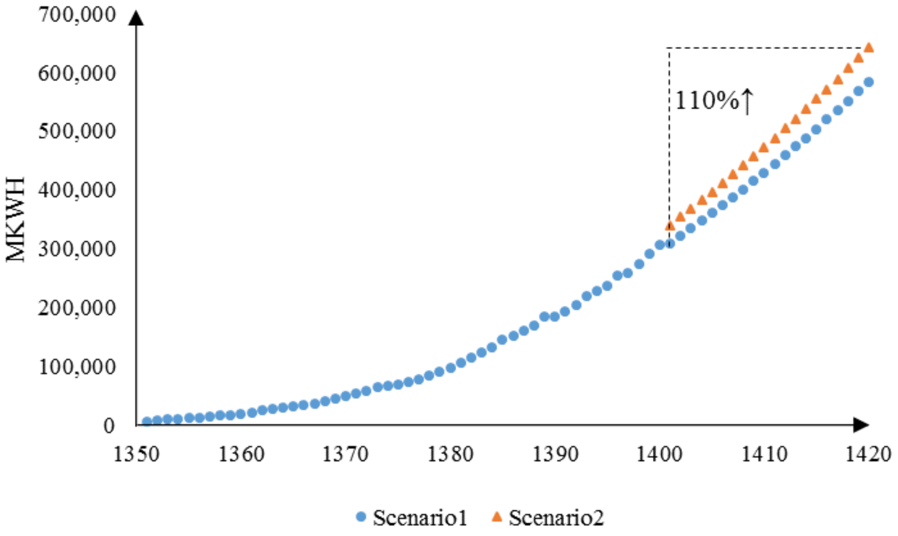
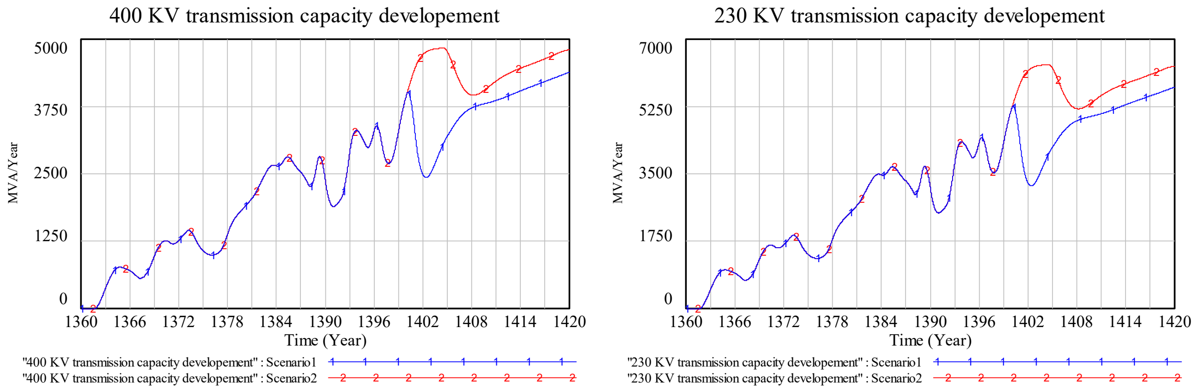
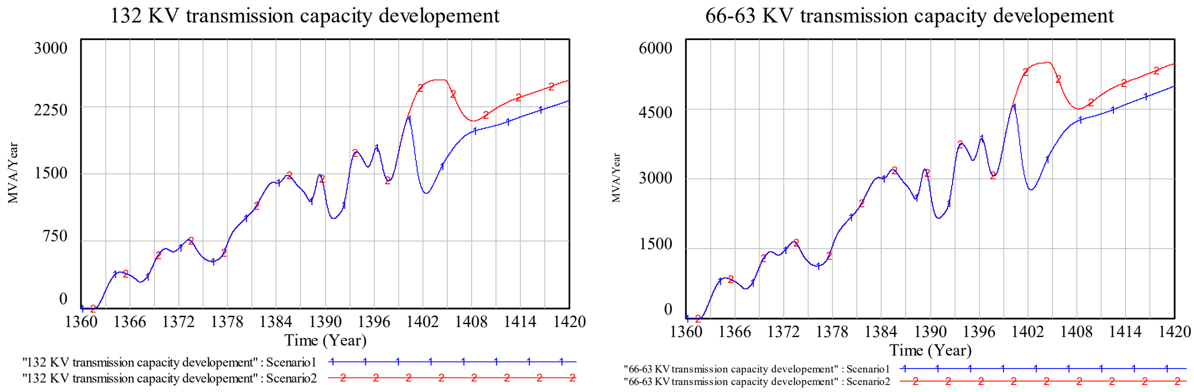


Figure 25. Prediction of country's electricity consumption based on a pessimistic trend

By implementing this scenario, the results shown in Figure 26 are achieved. These findings suggest that if electricity demand follows a trend with a steeper slope than the current conditions, there will be a substantial requirement for enhanced transmission capacity. In this scenario, the improvement policy is described as 400, 230, 132, and 63-66 KV transmission capacity need to increase by 108%, 133%, 136%, and 131%, respectively, as well as an overall increase in transmission capacity by 126% to 1420 compared to 1400.



(a) (b)



(c) (d)

Figure 26. Transmission capacity behavior by the two scenarios: (a) 400 KV; (b) 230 KV; (c) 132KV; (d) 63-66 KV

7.4. Scenario 3: Decrease in electricity demand trend (optimistic scenario)

Contrary to previous scenarios, in scenario 3, electricity demand is assumed to decrease by 10% each year from 1401 onwards. In this scenario, electricity demand follows a quadratic trend, as shown in Figure 27.

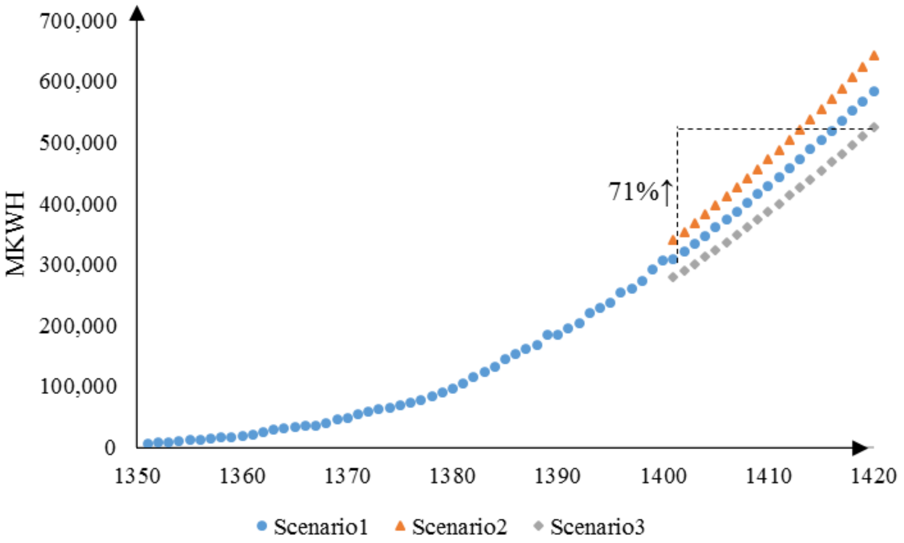
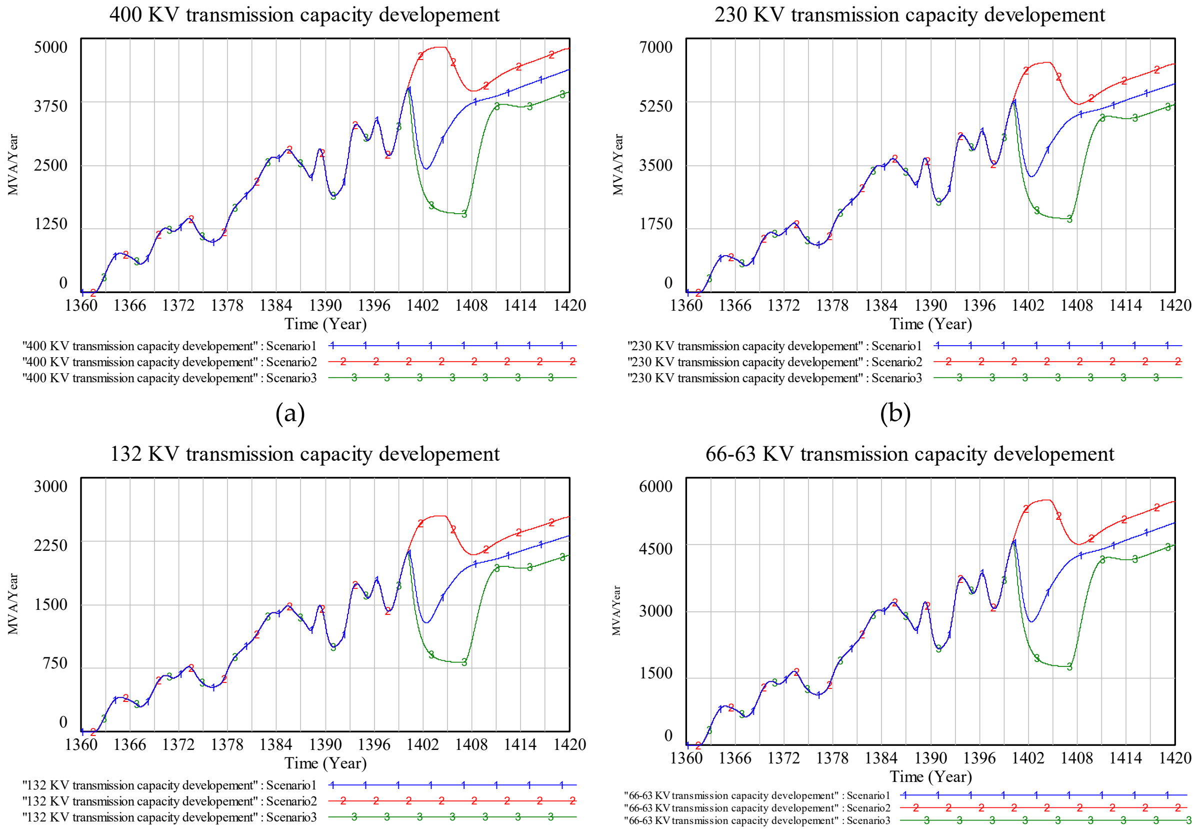


Figure 27. The country's electricity consumption prediction based on an optimistic trend

Under these conditions, the following results regarding model variables are obtained. The results show that if demand decreases by only 10% each year compared to scenario 1, the construction of transmission capacity until 1408 may decrease, and after that, construction should start to increase according to the trend presented in Figure 28.



(a) (b)

(c) (d)

Figure 28. Transmission capacity behavior by the three scenarios: (a) 400 KV; (b) 230 KV; (c) 132KV; (d) 63-66 KV

Finally, the outcomes of simulating the scenario of optimistic scenario, as depicted in Table 3, indicate that an expansion of 85%, 70%, 91%, and 94% in the transmission capacities of 400, 230, 132, and 63-66 KV is required to meet the low incremental slope of the electricity demand within the network.

Table 3. Results of implementing 3 research scenarios

Variable	1400	Moderate scenario (In 1420)		Pessimistic scenario (In 1420)		Optimistic scenario (In 1420)	
		Value	Change*	Value	Change	Value	Change
Total transmission capacity	295,642	607,793	106%	668,512	126%	547,020	85%
400 KV	80,203	151,322	89%	166,591	108%	136,039	70%
230 KV	94,318	200,137	112%	220,152	133%	180,103	91%
132 KV	38,360	82,504	115%	90,566	136%	74,435	94%
63-66 KV	82,761	173,829	110%	191,202	131%	156,441	89%
The difference between the required and the created capacity	24,125	23,007	-5%	25,000	4%	20,700	-14%

* The unit of variables is MVA and in the scenarios, the percentage of change compared to the year 1400 has been calculated.

8. Conclusion

Due to the abundance of influential variables in the electricity transmission industry, short-term and long-term planning regarding the amount, timing, and location of construction has always faced multiple challenges. This research, while reviewing previous domestic and foreign studies, provides a suitable framework for analyzing policies related to investment in the transmission industry. The subsystem diagram of this research considers inflation, demand, and electricity supply variables. In the causal loop diagram, important variables such as available transmission capacity, equipment depreciation, equipment age, and the probability of transformer burning are considered, and direct and indirect relationships between them are modeled. Subsequently, a stock and flow diagram is drawn, and after entering the mathematical relationships between the variables, simulation and validation of the model are performed. The results of reconstructing the historical behavior indicate a high accuracy of over 90% in simulating the behavior of transmission capacities over the past 40 years. After validating the model, three scenarios are simulated based on the growing demand trend. To define scenarios, initially, the trend of electricity demand in the country was determined by separating industrial, residential, agricultural, and other electricity uses. In the first scenario, it was assumed that the demand trend would increase as in the past. In these conditions, the country's electricity demand is projected to increase by 90% by the year 1420 compared to 1400. This finding, which is the result of the current research statistics, should be taken into consideration by the experts and decision-makers in the electricity industry. In the second scenario, it was assumed that electricity demand would be 10% higher each year compared to the predicted trend in the first scenario. In the third scenario, it was assumed to be 10% lower.

The results show that if the total transmission capacity by 1420 increases by less than 85%, the country will face a shortage of transmission capacity. Furthermore, if the total transmission capacity increases by 126%, it will fully cover electricity consumption demand, even if the demand growth rate is 10% higher than continuing the trend. However, if we want to cover the current growth trend in electricity demand in the country until 1420, the total transmission capacity must increase by 106%.

It is worth noting that the system dynamics approach is a powerful tool for analyzing complex systems and understanding their behavior over time. However, it has limitations when it comes to managing unforeseen disruptions, such as technological changes or significant policy shifts. As a result, the numerical results obtained are based on the assumption that sudden shocks do not impact the country's electricity distribution system.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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