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Studying the Dynamic Effects of Natural Gas Prices on Supply Security, a Systems Approach

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Abstract:
ensuring a reliable energy supply and demand system with appropriate growth is the main concern of any country for its comprehensive development. Domestic energy prices play an important role in energy security by controlling demand growth, and by incentivizing investments in energy resources development. In this paper, a simulation model is developed to explore how determining different prices of natural gas for various domestic demand sectors, i.e. differential pricing, affects supply security. The domestic natural gas consumption is categorized in four groups of the residential, power plants, industrial and transportation, and the dynamics between prices, supply and demand are modeled using a system dynamics model. The model is applied to a case study and various pricing policies and their influence on natural gas income and production are explored, and the minimum price growth for each sector that provides supply security is proposed.

Index Terms—Energy Pricing, Natural Gas, System Dynamics, Supply Security.

I. INTRODUCTION

Energy has an important and vital role in the social and economic development of countries. Ensuring a reliable energy supply and demand system with appropriate growth is the main concern of any country for its comprehensive development. This is not possible without energy planning at different levels such as a production factory, an industry or at local, national and international levels. Developing policies for a better performance of national energy system in future is very crucial for every country.

Natural gas (NG) is an important primary energy resource in different countries and among fossil fuels, has the most prospects of growth until 2035 [1]. NG is a promising fossil fuel with the potential to help transition to a lower carbon energy future. It is the least polluting fossil fuel with flexibility that can meet multiple energy demands in the countries' energy system [1, 2]. Natural gas is a favorable fuel for electricity generation, and gas-fired power plants are attractive because they are flexible, can be turned on and off very quickly at low cost, and have well known and relatively cheap technology for base load

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electricity production [3, 1]. In the move towards a greener future, NG plays various roles in different regions [4]. It can serve as a cleaner substitute for coal or petroleum products or as a backup fuel for countries with a higher share of renewable energies to balance intermittent electricity generation.

The role of natural gas in future energy supply as a cleaner substitute for coal and petroleum products has been investigated in the literature. Paltsev et al. developed a computable general equilibrium (CGE) model for US regional gas to investigate gas production and use in the US according to several future uncertainties related to emission-reduction policies, changes to the cost of producing non-conventional gas, production cost reductions for renewable energy and carbon-capture technologies, and the creation of a global natural gas market. Their results show a very favorable outlook for natural gas in the next decades, especially in the electric power sector. It is projected that natural gas share in total energy consumption will be higher in 2050, even under stringent greenhouse gas emission-reduction policies [4].

Earlier studies on NG supply-demand modeling generally dealt with the importance of a country's natural gas reservoirs' development for domestic consumption. DeAnne and Mashayekhi proposed a linear optimization model for natural gas planning, named Gas Planning Model (GPM) [5]. Boucher and Smeers used GPM for the development of natural gas fields in competition with other energy resources and gas imports to evaluate the optimal development of gas fields in Indonesia. They studied the possible competition between different energy carriers on demand side, especially in power plants [6]. Dayo and Adegbulugbe used a mathematical model for natural gas supply and demand in Nigeria. Their results showed that even in the low-growth scenario of energy consumption in Nigeria, natural gas consumption will be increased several times [7].

Another group of studies has worked on energy prices, varying from calculating the different sector's elasticity of NG demand to price [8, 9], to investigating how energy prices affect macroeconomic variables [10, 11, 12, 13, 14]. Subsidies on energy prices and maintaining a tight control of them are some tools many governments use to help the low income groups to have access to modern appliances and improve the level of welfare [15]. These policies, while providing all residents access to affordable energy, result in inefficient levels of consumption and overuse of energy, and consequently threatens energy supply security [16]. In this paper we study NG prices and their effect on NG production and supply security. We explore how determining different prices for various demand sectors (i.e., differential pricing), including the residential, power plants, industrial and transportation affects NG production and total domestic NG demand based on each sector's demand elasticity to its own price. Moreover the dynamic effects of these prices on total NG income, which contributes to financial resources required for development of NG resources is studied through a system dynamics model.

II. Modeling

A. Methodology

A model is a simplification of a real system and enables the modeler to study or forecast the future behaviour of the real system. A model generally simulates two aspects of the behavior of the original system. The first is the description of a system at a particular moment in time, using indicators, concepts and variables that are sufficient for this aim. But the state description is not enough, because the other purpose of the model is to simulate the behavior of the main system variables over time. Therefore, knowing the state of a system, the description of the other component, studying how the system changes over time and in which direction changes are also necessary. Modeling the relationships between system's components, rules that change the system's components, and the time functions according to which these elements change are used for this purpose. This is the second function of a model that acts as a simulation driving engine, because it helps to study how a system evolves over time, assuming the initial state of the system [17].

In this paper, a system dynamics method is used to model a natural gas supply-and-demand system, to forecast the future behavior of the main variables, and to analyze corrective policy options. One of the main features of using system dynamics is the causal-loop diagram that attempts to explain the structure of the problem through the effect of the causal variables and feedback loops. The relationships between sub-systems and their interactions can be clarified and visualized by a causal-loop diagram. In this diagram, the variables are presented as a set of nodes, and the relationships between variables are represented by arrows. There are signs at the end of arrows. If the increase in the first variable causes and increase in the second variable, the sign is positive, and if causes a decrease in the second variable, the sign is negative. The stock and flow diagram transforms descriptive relationships into a quantitative model through differential equations. A stock variable is represented as a rectangular box and a flow variable is a flash with a valve on it that enters the stock variable. The stocks are the representative of the inflow and outflow variables that are accumulated over time. Clouds represent the sources and the ends of the structure, which explains the boundaries of the model (Fig. 1).

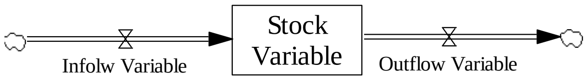


Fig. 1. Stock and Flow Variables

B. The Model's Causal Loop Diagram

The developed model studies the supply and demand side of natural gas industry simultaneously. The main model's variables and their interrelationships shape the causal loop diagram of the model which is depicted in Fig. 2. One of the main functions of the causal loop diagram is to develop the closed loops, i.e., reinforcing and balancing feedback loops of the system's structure. A cycle in which the effect of a variation in any variable propagates through the loop and returns to the first variable, reinforcing the initial deviation is a reinforcing loop. In the opposite way, a cycle in which the effect of a variation in any variable propagates through the loop and returns to the first variable, deviating opposite to the initial one is a balancing loop. When the number of negative signs in a loop is even, the loop is a reinforcing one and when odd, the loop is a balancing one.

One of the main dynamics in shape of reinforcing loops modeled in this paper is the effect of income made by selling natural gas to various demand sectors at different prices in providing financial resources for more development of natural gas so as to enable the country in supplying the increasing domestic NG demand. These loops are shown with positive signs in Fig. 2. For instance, the first loop indicates that more NG production enables more NG allocation to the residential sector, which results in more NG income and consequently increases the total NG income and the *Cumulative Income*. More cumulative income enables the country for more investment in developing the natural gas reserves. The *Developed Reserves* are NG reserves that can be used for production whenever required. More Developed Reserves enable the country to increase NG production.

Three negative or balancing loops are also depicted in the causal loop diagram. The first one indicates that more NG production reduces the volume of developed reserves. The second negative loop shows that with more NG production there will be more operational costs which reduces the amount of cumulative income. With a reduction in the cumulative income, less financial resources will be available for developing the NG reserves (the third negative loop).

III. SIMULATION AND RESULTS

A. Simulation

In system dynamics modeling, the causal loop diagram which is a descriptive model is converted to a quantitative model using differential equations. These equations indicate how a variable changes as a function of changes in its input variables during the time. The data used for the quantitative model is the supply and demand data of natural gas consumption and production in Iran. Due to large natural gas resources in Iran, about 60% of primary energy is supplied by natural gas. Before developing NG infrastructure in Iran, the main energy resources were oil products which were used domestically and exported to other countries. Based on the forecasted increase in domestic energy consumption, the policy makers decided to reduce the amount of domestic oil consumption by substituting it with natural gas in order to maintain the crude oil export level.

NG is sold at very low prices to various domestic sectors and this direct NG income is not enough for NG infrastructure development, and the crude oil export income provided by substituting NG with oil products has provided financial capital. This substitution growth is very steep from 2001 to 2011, but will level off after that. Therefore, it is projected that there would be a problem in supplying the entire growing NG demand in future [5]. Applying the developed NG supply and demand model to this case study, we explore how determining different NG prices for each domestic demand sector, having specified demand elasticity to price affects supply security.

The energy demand and NG share in each sector, including the residential (RES), power plant (PP), industrial (IND) and Transportation (TRN) sectors are estimated through explanatory variables such as family income (*FI*), urban percentage (UrP), population (POP), gross domestic product (GDP), productivity index (PrI), NG price (NG_P), NG substitute price (NG_Sbs_P), pipeline length (PPL) and NG power plants capacity share (NG_PP_CAP). The equation used for estimating energy consumption is a log-linear equation which takes the following form: $Y = \exp(\alpha_1 + \alpha_2 \ln(x_1) + \alpha_2 \ln(x_2) + ...)$ [18]. Equations 1 to 7 represent the demand functions. Equations 1 to 4 estimate the energy demand in the residential, power plants and industrial sectors respectively; and equations 5 to 7 represent the natural gas share in each sector. Multiplication of energy demand by natural gas share determines NG demand. Table 1 shows the statistical results. Since the variables are time series and some of them are non-stationary, co-integration tests were applied before estimating equation's coefficients.

Two important explanatory variables in determining demand equations are NG price and NG substitute price for each sector. Therefore, the elasticities and cross elasticities are important parameters in these equations that affect each sector's demand. The data of NG demand from 1985 to 2015 is used for estimating the coefficients in the equations. Since usage of Compressed Natural Gas (CNG) in the transportation sector in the case study started only recently (2003), there is insufficient data for estimating the CNG share equation. Although several studies have explored the elasticity of transportation demand to gasoline price [19, 20, 21], far fewer studies deal with cross sectional elasticities between gasoline and a substitute fuel, and to the best of our knowledge, no study measures the cross elasticity of gasoline and CNG for automobiles. Therefore, based on a study in Brazil, the cross elasticity between gasoline and ethanol is used for CNG [22, 23].

TABLE I. STATISTICS FOR ENERGY DEMAND AND NG SHARE EQUATIONS IN THE CASE STUDY

Y	Prob. α_1	Prob. α_2	Prob. α_3	Prob. α_4	R^2	Cointegration test Prob.
RES/POP	0.0000	0.0827	0.0001	−	0.929627	0.0113
PP/POP	0.0000	0.0000	0.0041	−	0.925530	0.0381
IND	−	0.0000	0.0001	−	0.898728	0.0147
TRN/POP	0.0000	0.0223	0.0000	−	0.980960	0.0009
RES_NG_Share	0.0000	0.0164	0.0029	0.0000	0.946464	0.0000
NG_Share_PP	0.0000	0.0052	0.0000	0.0060	0.871640	0.0007
IND_NG_Share	0.0005	0.0349	0.0052	0.0003	0.906209	0.0000

$$RES / POP = \exp(-13.68834+0.188108 \times \ln(FI) + 3.092696 \times \ln(UrP) - 0.134777 \times \ln(RES\_En\_P)) \quad (1)$$

$$PP / POP = \exp(-16.13413 + 5.339417 \times \ln(UrP) - 0.017731 \times \ln(PP\_En\_P(-1))) \quad (2)$$

$$IND = \exp(1.089464 \times \ln(GDP(-1)) - 0.592755 \times \ln(PrI) - 0.058591 \times \ln(IND\_En\_P)) \quad (3)$$

$$TRN / POP = \exp(-12.16145 + 0.119536 \times \ln(FI) + 2.911144 \times \ln(UrP) - 0.046780 \times \ln(TRN\_Oil\_P)) \quad (4)$$

$$NG\_Share\_RES = \exp(-3.78536 - 0.151513 \times \ln(NG\_P\_RES) + 0.250917 \times \ln(NG\_Sbs\_P) + 0.372612 \times \ln(PPL)) \quad (5)$$

$$NG\_Share\_PP = \exp(-2.54743 - 0.060203 \times \ln(NG\_P\_PP(-1)) + 0.213825 \times \ln(PPL) + 1.41817 \times \ln(NG\_PP\_CAP(-1))) \quad (6)$$

$$NG\_Share\_IND = \exp(-4.35454 - 0.402482 \times \ln(NG\_P\_Ind(-1)) + 0.210243 \times \ln(NG\_Sbs\_P(-1)) + 0.312932 \times \ln(PPL)) \quad (7)$$

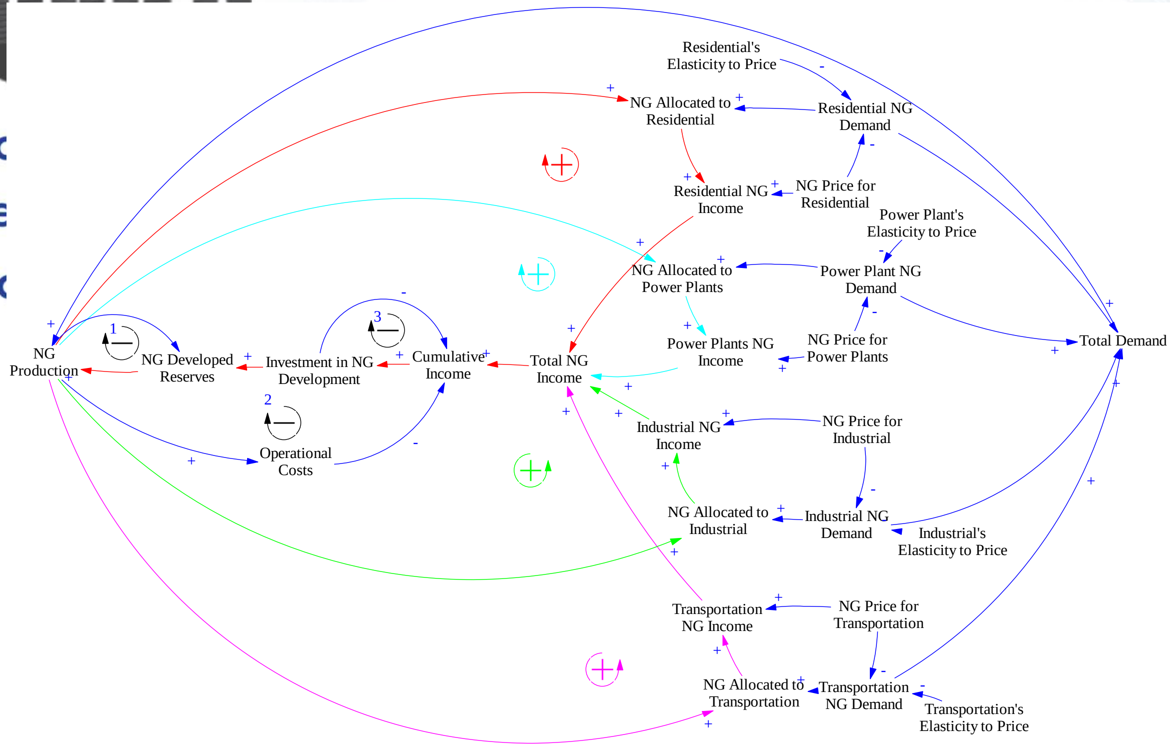


Fig. 2. Model's Causal Loop Diagram

IV. RESULTS

The developed model is simulated using Vensim software from 1985 to 2040. The model should be validated to be useful for studying the future behaviour of the system. The structure of natural gas system which is modeled descriptively with causal loop diagrams and mathematically through stock and flow diagram should be able to regenerate the historical data, which is one of the validation methods [24]. The results show acceptable compliance with historical data and make the model useful for forecasting the future and analysis of policy options.

As depicted in Fig. 2 and in Equations 1-7, natural gas demand is affected by price through elasticity of demand to price. Therefore NG price and the elasticity of NG demand to its own price directly affects energy demand which influences the amount of natural gas that is allocated to each demand sector. Therefore, when a consumption sector's price increases, its demand decreases and that sector's NG income changes according to the amount of increase in price and its effect on demand based on that sector's elasticity. More income increases the cumulative income which can be used for investment in more development of NG resources and NG supply. Therefore the yearly growth of each sector's price is an important variable for determining the supply security of the system.

As the Base Scenario (BSc) case, we assume that the NG price of each sector, as the model's decision variable, continues the past trends. In this case, the simulated model forecasts a gap between supply and demand in 2021, which means that the country cannot supply the entire increasing domestic demand, as shown is Figure 3.a. Based on this analysis an increase in the yearly price per cubic meter of natural gas in each sector is explored to see how it affects supply security. Finding the best value of policy variables requires various types and iterations of scenario analysis, and trial and error simulation, which can be a hard task. For this purpose, automatic optimization methods can be used to traverse the policy space in a simulation model [25, 26]. This analysis is an optimization simulation which uses optimization techniques in the simulation model according to defined objective functions and decision variables.

We explore how each sector's domestic NG price should increase to enable the government supply the entire domestic NG demand in four experiments and compare the results with the base scenario. In the optimization process our objective is to empower the country in supplying total domestic natural gas demand. Therefore the objective function is defined minimization of shortage costs (Equation 8). By considering a very large negative value as a penalty for shortage, the model tries to eliminate the gap between supply and demand. Since some governments try to keep the energy prices low to provide all residents an easy access to energy and increase the society's welfare level, the other objective function is to minimize the domestic NG prices growth (Equation 9).

$$\min ShC = \sum_{t=st}^{T} (S_t - DD_t) \times Pl \quad (8)$$

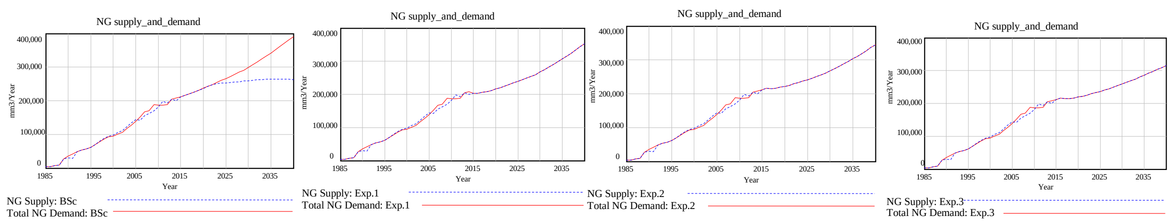
$$\min TPG = \sum_{t=ct}^{T} \sum_{i=1}^{4} PG_{it} \quad (9)$$

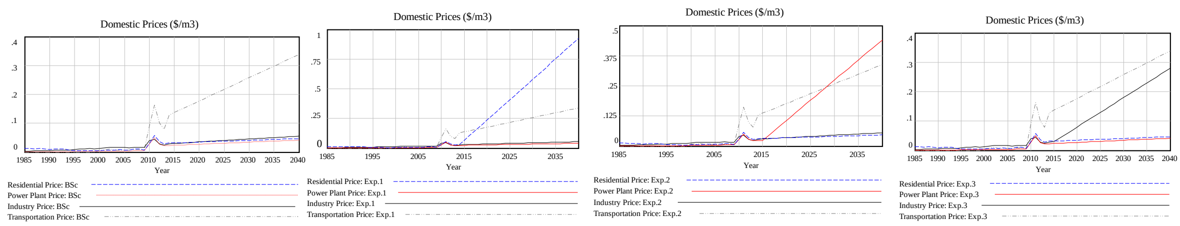
ShC: Shortage Cost,
S_t: Supply in period *t*,
DD_t: Domestic Demand in period *t*,
Pl: A large penalty for shortage,
TPG: Total Price Growth,
PG_{it}: Price Growth of Sector *i* at period *t*,
i:1 to 4, indices for each demand sector, 1 for the residential, 2 for the power plant, 3 for the industrial, and 4 for the transportation sector.
ct: the current time period when the simulation is performed for the future.
T: the final time period.

In experiment 1, we keep all sectors' but the residential sector's NG price the same as BSc to find the minimum growth rate of the residential sector's price so as to be able to fill in the gap between supply and demand. The same experiment is performed for the power plants and industrial sectors in experiments 2 and 3 respectively. Therefore, in experiments 1 to 3 the objective function is to minimize the shortage between supply and demand (Equation 7) and the decision variable is the yearly price growth of the residential sector in experiment 1, power plants in experiment 2 and the industrial sector in experiment 3. The model's results show that the minimum annual price growth rate should be 0.02, 0.017 and 0.007 $/cubic meter for the residential, power plants, and industrial sectors in Exp.1 to 3 respectively (Table 2).

The price growth and the supply and demand curve in all experiments are depicted in Fig.3. In BSc, the total domestic demand is more than total NG supply in 2021 and after, and the entire domestic demand cannot be supplied. In experiments 1 to 3 the total domestic demand will be met by the domestic NG production, as shown in the first row of Fig.3.b to 3.d., but at different costs, which are the sector's NG price growth. As it can be seen in the second row of Fig. 3, in Exp.1 to 3, two out of three domestic sector's NG prices are the same as BSc, and the third sector's NG price is different from the BSc. The residential sector's price growth in Exp.1 should be much higher than the industrial sector's price in Exp.3, and even more than the power plants price in Exp.3.

The different value of price growth for each sector is because of unequal elasticity of each sectors to price changes. The price growth of each sector decreases that sector's demand differently, according to the value of the sector's demand elasticity to its price. In this way, the price growth affects total demand. Moreover, the prices growth provides financial resources for development of natural gas and affects NG supply. On the other hand, the second objective function keeps the total price growth low. Therefore, the optimization process should decide how various sectors' NG prices should change annually to reach the aforementioned objectives. For example, among sectors, the industrial sector has the highest price elasticity, which means that with the same price growth of the sectors, the industrial sector's demand decreases the most. This sector contributes 27% of the entire NG demand in 2015 and its price increase has a major role in reducing the total NG demand.





(a) (b) (c) (d)

Fig. 3. Price paths in a) BSc, b) Exp.1, c) Exp.2, and d) Exp.3

Accordingly, in the fourth experiment, the optimum combination of all sectors' price growth is determined. Equations 8 and 9 are considered as the objective functions, and the decision variables are each sector's price growth in this experiment. The results of experiment 4 is shown in the sixth column of Table 2, indicating that the power plant sector's price growth should be the minimum, after that is the residential sector and the highest growth rate is for the industrial sector (Table 2, Exp.4). The industrial sector has the highest elasticity to price and its unit growth decreases this sector's demand the most compared to other sectors. The total yearly price growth of all sectors is 0.00898 dollar per cubic meter which is less than experiments one to three in which just one sector's price has been increased more than base scenario.

TABLE II. EACH SECTOR'S NG PRICE GROWTH IN EXPERIMENTS 1 TO 4 (DOLLAR/CUBIC METER), EXP. STANDS FOR EXPERIMENT

Sector	Base Scenario	Exp. 1	Exp. 2	Exp.3	Exp.4
Residential	0.00058974	0.02	0	0	0.002185
Power Plants	0.000720093	0	0.017	0	0.001524
Industrial	0.00101413	0	0	0.009	0.005271
Shortage	Yes	No	No	No	No
Total yearly Price Growth	0.002324	0.02	0.017	0.009	0.00898

V. CONCLUSION

Natural gas is an important energy resource with prospects to supply one quarter of the world energy demand by 2040. Ensuring a reliable NG supply is vital for every country's long term economic and social planning. In this paper we develop a dynamic model for natural gas system to study supply security via pricing policies. By developing a system dynamics model for natural gas supply and demand, the relationship between natural gas income and its effect on natural gas development and production activity is investigated. Also, the dynamic effect of each sector's price on that sector's demand is modeled. Using the developed model, we explored how each sector's natural gas price should increase to guarantee the energy supply security, while keeping the prices low as much as possible using optimization methods in our simulation model.

The model is applied to the case study of Iran, in which natural gas contributes to over 60% of its primary energy. About 30 years ago Iran's government decided to develop natural gas infrastructure, supply the increasing domestic energy demand with natural gas and substitute it with petroleum products which were the main primary energy resource at that time. Keeping natural gas prices low has been a policy pursued to encourage replacement of natural gas with petroleum products and to enhance all residents' access to cheap energy like many other countries with access to low cost energy resources. The model's results predict that continuing the current trend in NG pricing for these sectors does not provide sufficient capital for more investment in NG infrastructure and threatens the country's energy supply security. The optimum price growth of each sector that ensures supply security is suggested using simulation optimization methods.

While the presented model has a mathematical background, it can be turned into a framework that is very easily usable by policymakers to change various parameters and variables and to explore their long term direct effects, side effects and the dynamics they create.

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