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Investigating the cost-effective energy efficiency practices with mitigated rebound: the case of energy-intensive industries

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ABSTRACT

Energy efficiency enhancement is considered a solution for enhancing energy conservation and sustainability. The present study deals with two major challenges in improving energy efficiency: the initial investment cost and the rebound effect. Funding of energy efficiency solutions and mitigating the rebound can be achieved through energy subsidy reduction. To be an effective policy, there must be a plan that considers the dependency between energy efficiency, avoided subsidy, and required funds for all efficiency solutions. Thus, there is a problem at the aggregate level of the economy whose roots are in engineering details.

The combination of a top-down dynamic general equilibrium model with a bottom-up efficiency improvement module is used to find the set of efficiency practices that should be realized in each period along with the required increase in energy prices. Choosing efficiency practices depends on their costs and the available funds that are retrieved from avoided subsidies in the previous period. The model is applied to the energy-intensive industries in Iran.

The model results show that using the recommended policy, over less than ten years, the energy efficiency of electrical and natural gas equipment in energy-intensive industries of Iran can be increased by 12.7% and 18.1% respectively. The rebound effect starts with values above 80% and then falls below 0% which indicates the success of the proposed policy in mitigating the rebound effect. Results also demonstrate that the implementation of the policy realizes the 4% reduction in CO_2 emissions by 2030 which is Iran's unconditional pledge.

Keywords

Energy efficiency improvement;
Subsidy removal;
General equilibrium model;
Rebound effect;

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1 Introduction

The industry and especially, the energy-intensive industries have a high share of energy consumption in the world. After allocating electricity and heat emissions to final sectors, i.e., accounting for the emissions associated with electricity and heat generation, the industry is found to be the largest emitting sector, with over 40% of global GHG emissions in 2019. [1]. According to the report of the latest energy balance sheet released in Iran, industries (excluding energy industries) consumed 2.3 TJ in 2019 [2].

Improving energy efficiency is regarded as an important solution to reduce energy consumption and mitigate climate change. In 2018 it was claimed that if all the available cost-effective energy efficiency potential are realized by 2040, the global energy intensity could be halved from 2018 levels by 2040. [3, p.27].

Literature on evaluating the effects of improving energy efficiency is vast. From an economic perspective, increasing energy efficiency may not be as successful as expected in reducing energy consumption. The reason lies in the fact that energy efficiency improvement reduces the effective price of energy which increases the demand for energy services. Therefore, part of the expected energy saving becomes offset [4]. This is

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*Corresponding author – e-mail: Z_Adel@sbu.ac.ir called the rebound effect. A wide variety of economic models has been employed to measure the magnitude of rebound at the sectoral and economy-wide levels. The economy-wide rebound captures all the price and income effects that might propagate throughout the economy as a result of increasing energy efficiency.

The studies on the economy-wide rebound can be divided into two categories based on their approach to introducing the energy efficiency in the model [5]. The first category which comprises the majority of economy-wide rebound studies is based on realized efficiency improvement, and too little or no explanation is given about how the efficiency is increased (in technical meaning) or how the energy productivity is improved (in economic terms). In these studies, energy efficiency enhancement is included using some aggregate parameters such as increasing energy productivity and autonomous energy efficiency improvement (AEEI). The trend of changes in these parameters is exogenously fed into the model and the associated effects are analyzed. Increasing energy efficiency is costless and thus the economics of energy efficiency increase is not fully considered.

The second category of studies is based on potential efficiency improvement, i.e., these studies estimate the rebound effect from an actual, typically costly, energy efficiency policy and are called policy-induced energy efficiency improvement [6].

The importance of including efficiency costs in rebound effect estimation has been highlighted in many studies. Greening et. al [5], who raised the issue of capital cost in rebound estimation, stated that measurement of the rebound declines in size due to explicit consideration of the capital cost of efficiency enhancement. Therefore, including costs of increasing efficiency may lead to a more precise estimation of the rebound effect.

The present study aims at investigating the economy-wide effects of increasing energy efficiency (in technical terms) based on the second approach. In addition to including the costs of efficiency practices, the novelty of the present paper is that it decides where the efficiency improvement should come from (in technical meaning). The efficiency solutions are based on viable previously studied efficiency potentials in the energy-intensive industries of Iran. The other novelty of the paper is that the model can prioritize energy efficiency potentials based on their costs and benefits and then implements them in the economic model.

The economic model is a general equilibrium model and has the capability of assessing the economy-wide effects of increasing energy efficiency. Computable General Equilibrium (CGE) models are the most appropriate approach to use in evaluating the economy-wide rebound [7]. As Greening et al. [5] note, ‘prices in an economy will undergo numerous, and complex adjustments. Only a general equilibrium analysis can predict the ultimate result of these changes.’

Because the required investment and the economy-wide response to implementing energy efficiency solutions are included in the model, the results of the model determine the set of energy efficiency potentials which should be realized each year along with the required investment and economy-wide rebound effect.

Determination of energy efficiency pathways can help analyze the rebound mitigation policies. For each year, the efficiency potentials and the reduction in the effective price of energy can be calculated.

Rising energy prices is one of the main solutions to deal with the rebound effect because it neutralizes the decline in effective energy price [8, 9]. Where energy is subsidized, this approach can reduce the energy subsidy and rebound effect simultaneously, and thus it is regarded as a win-win solution [10]. Given the dependency between the energy price and efficiency improvement, the use of mixed instruments creates synergy in reducing energy consumption. Using the combination of the financial instruments (such as pricing and taxation and increasing energy efficiency simultaneously, contributes to the correct pricing of energy as well as eliminating the rebound effect [11].

Birol and Keppler [12] define the policy of price change and the technology development of efficiency improvement as two faces of the same reality which should be developed together. Thus, the present study contributes to the current studies in two aspects. First, it determines the energy efficiency pathway and calculates the economy-wide rebound effect based on engineering details of energy efficiency solutions. Second, it determines a temporal subsidy removal plan that would mitigate the rebound effect. It is worth noting that the proposed approach in including efficient technologies and increasing energy efficiency is generic and can be applied to economic models that study the rebound effect.

The present study is organized as follows. Section 2 discusses the literature on the rebound effect and focuses mainly on the studies that deal with mitigating the rebound. Section 3 illustrates the model and the methodology for incorporating the proposed energy efficiency program. Results of the model are presented in section 4. Finally, section 5 concludes the suggestions in the field of evaluating the effects of energy efficiency improvement and discusses the policy implications of the present study.

2 Literature review

Most estimates of the rebound are based on realized rather than potential efficiency improvement, i.e., these estimates capture the trade-offs ex-post, and too little or no explanation is given to how to increase the efficiency (in technical meaning) or how to improve energy productivity (in economic terms).

There are numerous studies estimating the rebound effect of realized energy efficiency enhancement. Examples include Grepperud and Rasmussen who studied the rebound effect in Norway by interpreting efficiency improvements as exogenous factor productivity changes [13], a study by Broberg et al. in which the rebound effect was calculated in the Swedish economy as a result of a 5% exogenous increase in efficiency of industrial energy use [14], Wei and Liu who assumed that the energy efficiency in 2040 is 10% higher than the BAU case for all non-energy sectors in all regions of the world [15], Li et al. who studied the rebound effect associated with exogenous improvement in autonomous energy efficiency improvement (AEEI) parameter [16] and Lu et al. who assumed that energy efficiency of five types of energy carriers is improved by 5% and 10% in production sectors of China [17].

All these studies assume a costless efficiency increase. In addition, as Zimmerman et al. indicated in their study, the rebound effect must be assessed with attention to the relationship between energy and capital (complementarity/substitutability). Otherwise, the rebound would be overestimated [18]. A correct estimate of rebound is important especially in the energy-intensive industries and developing countries because the magnitude of rebound may be higher.

The rebound effect in energy-intensive industries is higher due to the higher share of fuel costs in these industries. Developing countries have a higher potential for the occurrence of the rebound effect, due to the non-saturation of energy consumption [18]. When the value of the rebound effect is high, relying only on efficiency improvement is not effective and other tools should be used to reduce energy consumption [19]. The literature on rebound mitigation is yet sparse [16].

Although applying mixed instruments in counteracting the rebound has a theoretical foundation, few studies have been conducted on the evaluation of the impact of using mixed instruments on counteracting the rebound effect. In a study performed in Austria, the energy tax was used to deal with the rebound effect [20]. The study evaluated the standardization of equipment along with energy tax as a useful instrument in reducing energy consumption in the household sector. It integrates the aggregate technological variables as a driver of energy demand.

In an attempt to study the effect of the revenue_ neutral financing of incentive efficiency programs from avoided energy subsidies, Gopal et al. [21] at Lawrence Berkeley National Laboratory (LBNL) used the LBNL Energy Efficiency Revenue Analysis model to estimate the amount of energy that can be saved in several emerging economies. They calculate the savings from avoided subsidies achieved through energy efficiency from an engineering perspective.

The benefits from energy savings and the savings from avoided subsidies are compared with the associated costs in the lifetime of chosen appliances in the household sector. As an example, the net present value of the savings from avoided subsidy as a result of 25% efficiency improvement for a 15-year lifetime refrigerator is \$150. Compared to the \$107 incremental cost of the efficient refrigerator, a government incentive result in \$43 savings from avoided subsidies. The amount of energy savings is corrected with the value of rebound that is exogenously given to the model based on literature estimates (e.g., an 11 % rebound for refrigerators). Although engineering details are accounted for, the economic interaction among agents is not included in the model.

Li et al. examined the impact of the subsidy elimination on the rebound effect by using a CGE model for China and suggested that renewable resources should be subsidized to reduce the adverse economic effects caused by eliminating fossil fuel subsidies [16]. They introduced the autonomous energy efficiency improvement (AEEI) parameter as an indicator of energy efficiency enhancement and set scenarios with different exogenous technology advancement levels from 1% to 7%. Following different subsidy removal programs, the calculated rebound range from 95.8% (no subsidy removal) to -23.1% (all fossil energy subsidy is removed, additional energy subsidy rate for some energy carriers).

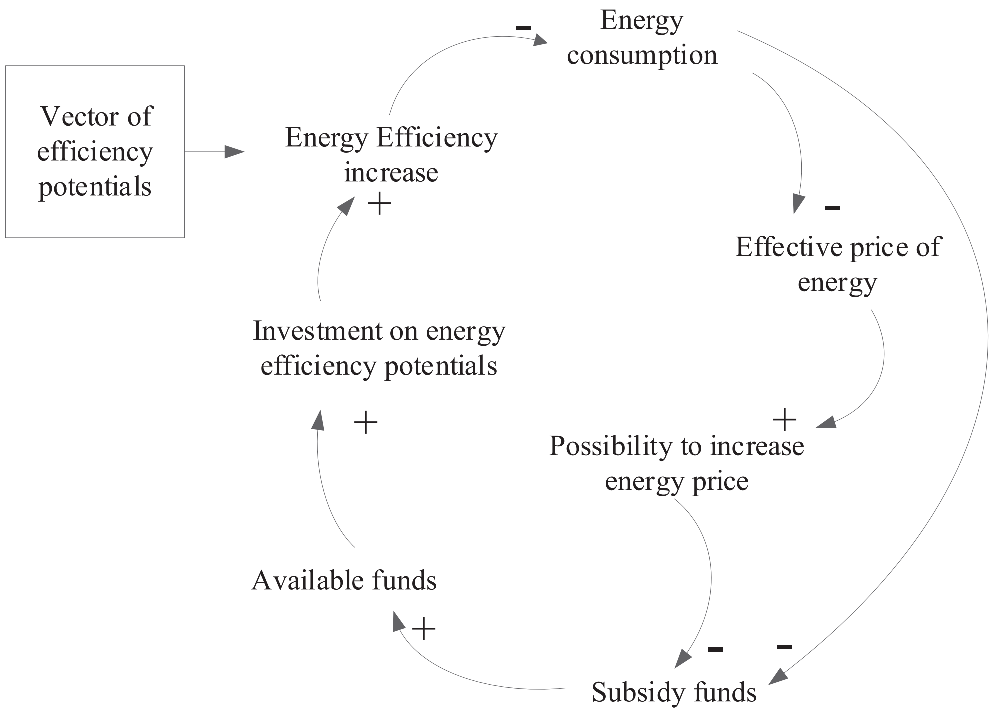

Figure 1: The schematic cause and effect diagram of the proposed energy efficiency plan

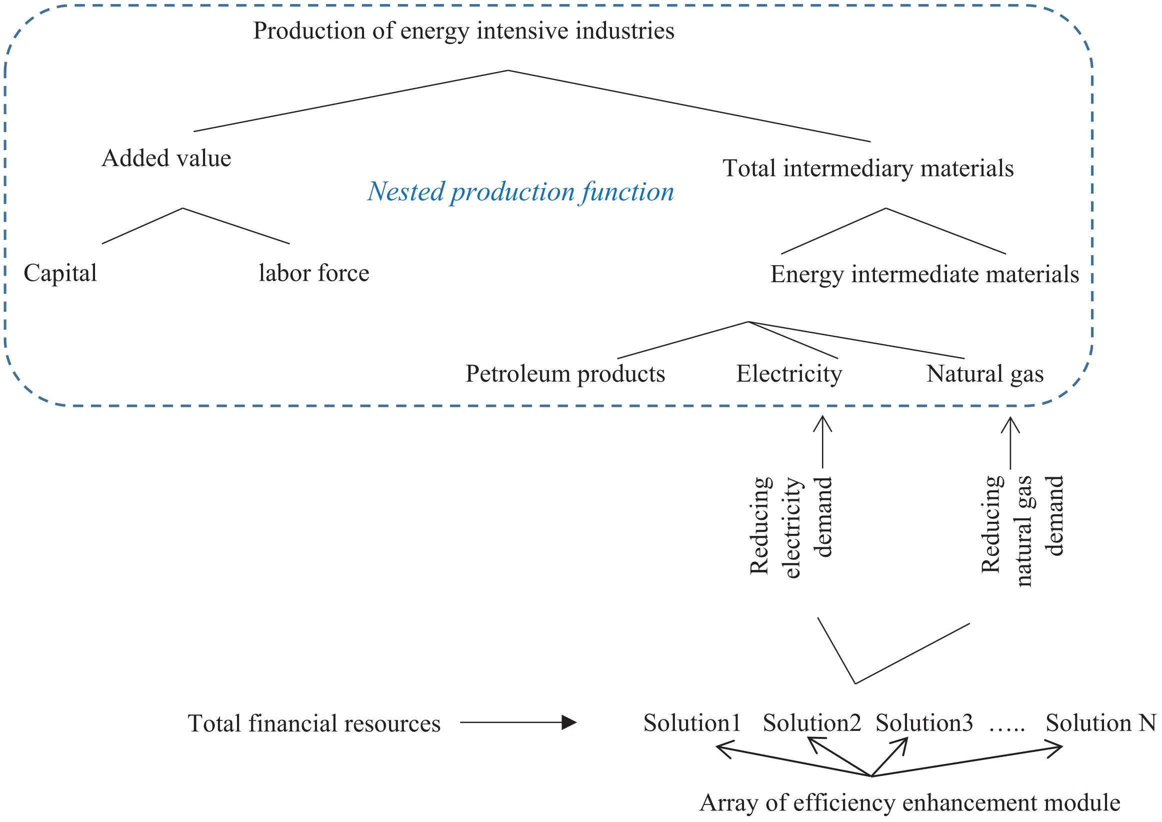

Figure 2: The relationship between the nested production function of the energy-intensive industries from the CGE model and the efficiency improvement module

Li and Lin [22] analyzed the impact of fossil-fuel subsidies on the rebound effects across Chinese sectors using the input/output model. They calculated the aggregate technological advancement in each sector from 2006- to 2010 based on the Leontief matrix of the Chinese input/output table. The rebound effect is then calculated based on the reduction in energy consumption and output growth promoted by technological advancement. Their analysis shows that the aggregate sectors' rebound effect without subsidy removal has been 11.31% and if the subsidies were removed, the rebound effects could have been 10.64%.

In addition, the technical aspects of increasing energy efficiency play a vital role in determining the level of efficiency enhancement. There is certainly a bound on the level of technically possible energy conservation and this bound varies across sectors.

3 Conceptual and Methodological frameworks

Theoretically, improving energy efficiency reduces the cost of provided energy services. Energy subsidies can be reduced to stabilize the effective price of energy. Avoided subsidies can be used as a source of financing for energy efficiency programs. The proposed program curbs the growth of energy consumption via decreasing the rebound and overcoming the first cost barrier in efficiency investment and can also reduce energy subsidies.

The suggested process of realizing energy efficiency potentials is described hereafter. Curtailing energy demand using energy efficiency increase initially requires comprehensive knowledge about energy efficiency potentials. Therefore, as the first step, the energy efficiency potentials in the energy-intensive industries of Iran are found and the corresponding costs (investment and O&M) and benefits (energy saving and emission reduction) are analyzed. The gathered information comprises an array of energy efficiency potentials. More detail on the array and efficiency potentials will be given in Section 3.1.

Depending on the available funds, efficiency solutions are chosen in a bottom-up manner and are then translated to a top-down general equilibrium model. The computable general equilibrium (CGE) model is an appropriate choice in analyzing economy-wide effects of efficiency improvement due to the consideration of different economic sectors, economic agents, and their interactions. An overview of the CGE model of Iran is presented in Section 3.2.

From an economic perspective, increasing energy efficiency reduces energy consumption. Because energy is subsidized, reducing energy consumption reduces energy subsidy payments. In addition, efficiency enhancement reduces the cost of energy services and this is the main driver of the rebound effect. To mitigate the rebound, a reduction in the cost of energy services should be neutralized. Thus, energy prices should increase (i.e., energy subsidies should be reduced).

Both the reduction in energy demand and energy subsidy release subsidy funds. The revenue from increased energy prices (avoided subsidies) can be used to finance the next group of selected energy efficiency solutions. The suggested process of realizing energy efficiency potentials is illustrated in Fig. 1. The process can be continued until all viable efficiency solutions are implemented. The production function of the general equilibrium model is modified to capture these effects.

To consider the technical details of the energy efficiency improvement projects, an efficiency improvement module is developed and linked to the dynamic general equilibrium model. The CGE model calculated the total volume of available financial resources that can be allocated to efficiency enhancement and the efficiency improvement module selects the energy efficiency improvement solutions based on the financial resource constraint. The total amount of energy savings and the change in the Leontief coefficients of the energy-intensive industries are determined in the efficiency improvement module and are considered as input data to the general equilibrium model.

Figure 2 displays the conceptual model of the relationship between the manufacturing section of the energy-intensive industries in the CGE model and the efficiency improvement module. A detailed mathematical explanation of the modifications is presented in Section 3.3.

3.1 Array of energy efficiency solutions

Energy efficiency solutions are specified as an array of discrete technologies. Barkhordar et al. [23] evaluated efficiency improvement potentials in energy-intensive industries of Iran including steel, aluminum, cement, brick, glass, and paper industries. Based on their study and the value of energy-saving potentials and their relevant costs, the efficiency improvement solutions for which the government is supposed to supply their financial resources are organized. There are 42 out of 79 efficiency opportunities that have payback periods under three years. Implementing all of the studied efficiency solutions is expected to save more than 110 peta-Joule. This is an engineering-based calculation of the energy-saving potential. A shortlist of selected solutions is presented in Table A1.

Various criteria for prioritizing projects are available, such as net present value (NPV) and Internal Rate of Return (IRR). In the current analysis, it is supposed that the government is concerned with energy-saving and emission reduction and it does not aim at making money from energy cost savings. Therefore, the financial flow of the benefits from the implementation of energy efficiency solutions is not transferred to the government. Instead, the amount of saved energy and the corresponding costs are important for the government in prioritizing solutions. The higher the energy saving from one dollar investment in energy efficiency practices, the better. The efficiency improvement solutions are ranked based on the energy-saving potential per unit of required investment.

It should be noted that energy can be conserved through different strategies. In some industries, saving energy may be accompanied by reducing capital, not adding investments. This is the case where the production process is changed. In such cases, energy and capital are complements. However, the present study only deals with energy efficiency solutions that save energy by replacing old technologies with more efficient technologies or by installing systems that increase the efficiency of a system. Hence, capital and energy are substitutes.

The array of energy efficiency solutions is fed into the CGE model. The structure of the CGE model is presented in the next section.

3.2 The general equilibrium model

The General Equilibrium Model of Iran's economy (GREMI) is a recursive multi-sector and dynamic model. The developed model is consistent with neoclassical general equilibrium models, as explained in [24]. The central core of the model is the static general equilibrium model explained in [25]. A detailed description of the model along with model validation is presented by Barkhordar and Saboohi [26]. The agents have comparative expectations. The reason lies in the fact that the assumption of complete knowledge of agents about the future, especially in a country where its economy is in transition, is not reasonable. Therefore, it is better to consider the agents' behavior in response to the policies as a comparative expectation. The effects of policy-making are examined from 2018-to 2030.

The CGE models have the advantage of considering all economic agents, their behaviors, and the financial transaction among them. Economic agents in the model are urban and rural households, 14 activities, the government, and the rest of the world.

Based on neoclassical foundations, households' demand for goods and services is determined based on their motivation toward maximizing their utility from consumption subject to their budget constraint. The linear expenditure system (LES) is used to represent household demand (Eq. (1)). In the linear expenditure system, the minimum subsistence requirement is imposed on each good. This subsistence parameter is considered a direct function of the population. Thus, unemployed people need to meet their minimum subsistence requirement although the revenue of employed persons supplies the expenditure of the whole people of the community. Therefore, it is assumed that the income of the employed people is primarily used to meet the minimum needs of all individuals, and then, the remaining value is divided among different groups of goods and services by constant ratios.

$$x_{i,t,h} = \beta_{i,t,h} + \frac{\alpha_{i,t,h}}{P_{i,t,h}} \times (\mu_{t,h} - \sum_{j=1}^{I} \beta_{j,t,h} \times P_{j,t,h}) \tag{1}$$

In which $x_{i,t,h}$ is the demand for commodity i by the household type h at time t. $\alpha_{i,t,h}$ is the share parameter, the $\beta_{i,t,h}$ is the subsistence bundle, and the $\mu_{t,h}$ is the household total expenditure. The value of demand parameters α and β are given in Table A2. The income-expenditure balance of households is considered an identity in the model. Households supply labor and their savings and earn income, pay tax and receive a direct transfer from the government.

Firms produce commodities and demand capital, labor, energy, and material. Firms try to maximize their profit subject to their production function. The production function of firms has a nested structure in which the primary inputs (labor and capital) are combined under the constant elasticity of substitution (CES) function and generate the added value of the firm. The intermediate inputs (materials and energy) are also combined based on a fixed proportion (Leontief production function) and constitute the total intermediate input (Eq. 2). Further, the total intermediate input and the added value of the firm are combined according to the Leontief production function. The nested production function is illustrated in Fig. 2.

Table 1: Efficiency improvement in energy intensive industries

Efficiency enhancement	2019	2020	2021	2022	2023	2024	2025
Electricity	1.53%	3.95%	5.22%	0.53%	0.38%	0.58%	0.41%
Natural gas	16.74%	0.11%	0.31%	0.54%	0.37%	0.00%	0.04%

$$QINT_{c,a} = ica_{c,a} \times QINTA_a \qquad (2)$$

Where:

$QINT_{a,c}$: Quantity of intermediate input c in production sector a
$QINTA_a$: Quantity of aggregate intermediate input in production sector a
$ica_{a,c}$: Leontief coefficient for intermediate inputs c in production sector a

$ica_{a,c}$ reflects the share of intermediate inputs in producing one unit of output. For energy carriers that are used as intermediate inputs to industries, this coefficient indicates how much energy is used in producing one unit of output. It is thus a measure of energy efficiency in economic terms. This is the main connection point between the efficiency module and the CGE model.

Energy productivity changes in response to energy efficiency improvement. The effect of the energy efficiency program on energy and capital productivity is explained in the next section.

The government is considered an agent who demands commodities, receives taxes, and makes investments. Given the difference in the incentives for governmental investment relative to the private sector, these two sectors and their dynamics are included in the model differently to reveal the effects of the non-optimal allocation of governmental investment in manufacturing activities on production.

For private sectors, the allocation of capital to each sector is determined based on its relative return to capital [27]. However, governmental investment is considered as the allocation of a certain share of the development budget to various sectors such as services (defense, public health, etc.), oil and gas, and industry. In contrast, the private sector investment is a function of the profitability of manufacturing units in the past period.

The CGE model clears markets for commodities and primary factors by finding a vector of prices that equals the aggregate demand with the aggregate supply. The rest of the world is considered as the origin of imports to and destination for export from a country. The current account is considered in the model to balance the supply and demand of foreign currency. The CGE model presented so far is not adapted to include the efficiency solutions. It should be further modified to include the mechanism of the efficiency program. The economic challenge of specifying energy efficiency solutions in the CGE model is discussed in the next section and the proposed solution is elaborated.

3.3 Representation of energy efficiency solutions

Engineers choose among different technologies based on technical details of the technologies. There is always a criterion such as a project cost or the project benefit that should be minimized or maximized. The energy and mass balance are usually included in engineering models. For an end-use technology, the energy balance can be stated as a relationship between the energy input of the technology (Final Energy) and the useful energy that the technology provides (Useful Energy). (Eq. (3))

$$Useful\_Energy = \eta \times Final\_Energy \qquad (3)$$

Where η is the physical energy efficiency of the technology. The formulation looks similar to a Leontief production function. In increasing the energy efficiency of a production process, there is a trade-off between energy and capital. The decision about whether to invest in an energy efficiency solution or not is made based on maximization or minimization of the chosen criteria, such as cost minimization of the process.

Economists, on the other hand, use production functions to show the aggregate relationship between real output and input factors. The production function is commonly used to represent a production process. A suitable production function should be able to depict the range of substitution possibilities. The parameters of the function are measured from real data using regression analysis. Using the regression results for the future requires the assumption that the underlying production function causing the relationship between the input factors and real output is valid beyond the range of the historical data. The validity of this assumption is questionable when efficient technologies are new or when increasing efficiency has not been a concern before and historical patterns do not have inside information about using existing efficient technologies.

When energy-efficient technology is new, Herring and Sorrel [7] suggest including technology parameters that can affect the inputs of production factors. The technology parameters depict how technology can make each input more effective in producing output by simply multiplying the inputs by a technology parameter. As they also mention on page 115, “the task of estimating the parameters of such (production) functions is also challenging”.

From an engineering perspective, using production functions for energy-saving studies has two challenges. First, non-linear production functions do not necessarily follow the law of conservation of energy. Second, the parameterization of substitution possibilities with highly aggregated production functions is difficult to validate empirically.

To resolve these issues, this study attempts to benefit from engineering details of energy efficiency solutions within an economic production function. Discrete energy efficiency solutions are ranked in an array of efficiency potentials based on their energy savings to cost ratio. In each period, a set of efficiency solutions are chosen depending on their energy savings to cost ratio. The total cost of implementing selected solutions should not exceed the efficiency funds provided by the government.

According to the technical specification of efficiency solutions, implementing the kth efficiency solution reduces energy consumption by ΔEE_k percent and requires investment equal to EEI_k. Implementing N_t efficiency solutions in year t results in a $\sum_k^N \Delta EE_k$ percent decrease in aggregate energy demand of a production sector. The aggregate energy demand in the nested production function of energy-intensive industries is represented by fixed (Leontief) coefficients.

Implementing energy efficiency practices reduces the energy demand per unit of output. To represent energy efficiency enhancement in the production function of energy-intensive industries, the Leontief coefficients of energy input ($ica^{Base}_{energy,a,t}$) in the baseline scenario (the scenario in which efficiency enhancement is not funded by the government and everything continues as it did in the past) should be multiplied by a productivity factor. (Eq. (4)) The productivity parameter (τe) is calculated each year after the implementation of energy efficiency solutions (Eq. (5)).

$$ica^{EE}_{energy,a,t} = ica^{Base}_{energy,a,t} \times \tau e_{j,t} \qquad j: types\ of\ final\ energy \tag{4}$$

$$\tau e_{j,t} = 1 + \sum_k \Delta EE_{k,j} \qquad k: energy\ efficiency\ solutions \tag{5}$$

Where $ica^{EE}_{energy.a,t}$ is the updated Leontief coefficient, $\tau e_{j,t}$ is the energy productivity factor that demonstrates how increasing energy efficiency could make energy input more effective in producing output. $\Delta EE_{k,j}$ is the percentage change in energy consumption due to the implementation of energy efficiency solution k.

Investment in increasing energy efficiency increases the capital stock of the production sector under the same quantity of real output. The capital productivity factor, $\tau k_{j,t}$, demonstrates how increasing energy

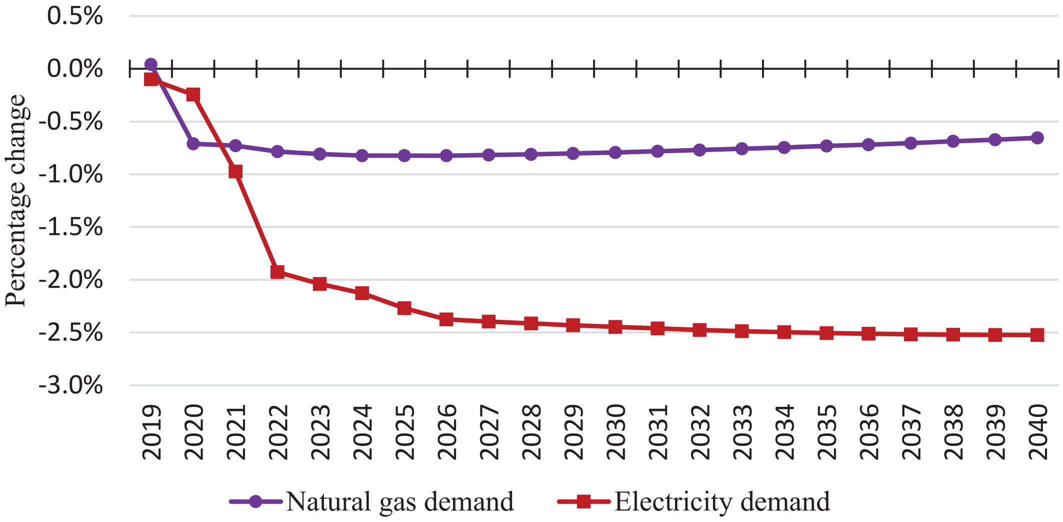

Figure 3: Percentage change in electricity and natural gas demand concerning the baseline scenario

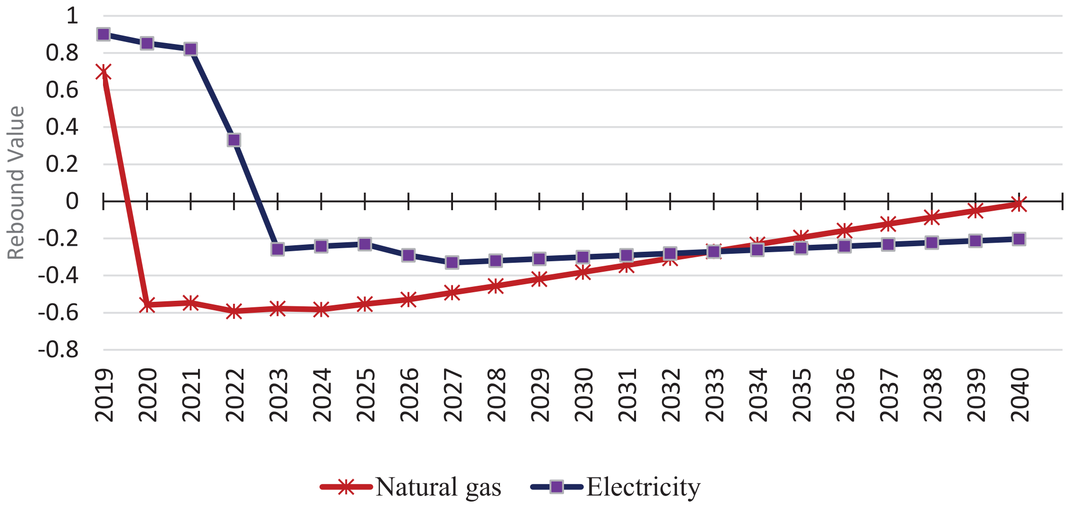

Figure 4: The economy-wide rebound resulting from the efficiency improvement of the electricity-consuming and natural gas-consuming devices in the energy-intensive industries

efficiency changes the productivity of capital in producing output. The capital productivity factor is derived from Eq. (6).

$$\tau k_{j,t} = \frac{1}{1+\sum_k I_{k,j}} \quad j: types\ of\ \ final\ energy, \quad k: efficiency\ solutions \tag{6}$$

Where $I_{k,j}$ is the required investment to implement efficiency solution k. The same can be defined for the labor productivity factor, $\tau l_{j,t}$, although in most cases efficiency solutions are assumed to be neutral concerning labor demand (i.e., $\tau l_{j,t} = 1$).

Considering the productivity factors, the general expression for the production function takes the form of Eq. (7). It should be noted that the productivity factors are endogenously calculated each year based on the selected efficiency solutions. This feature of the model enables it to find the optimum pathway for increasing energy efficiency.

$$QA_t = f\left(\tau k_t \times K_t, \tau l_t \times L_t, \tau e_t \times E_t, M \right) \tag{7}$$

In each period, the set of energy efficiency potentials is chosen such that the total amount of investment does not exceed the total available funds (Eq. (8))

$$the \sum_{k,j} I_{k,j,t} \le Fund_t \qquad j: types\ of\ \ final\ energy, \quad k: efficiency\ solutions \tag{8}$$

Except for the starting year of the efficiency program, where the amount of funds is supplied from the government budget, the total available fund is calculated based on the amount of avoided subsidies (Eq. (9))

$$Fund_t = \sum_j \Delta ED_{j,t}^{EE}.subsidy_{j,t} \quad j: types\ of\ \ final\ energy \tag{9}$$

Where $\Delta ED_{j,t}^{EE}$ is the realized energy demand reduction of energy-intensive industries and subsidy is the rate of energy subsidy for energy type j. In contrast to the expected energy demand reduction which is known a priori to model execution, the realized energy demand savings are determined based on model results. The success of the efficiency program in curtailing the demand is assessed using the rebound effect. In other words, the realized energy demand savings is equal to the expected energy demand saving corrected for the rebound effect. The calculation of the rebound effect is explained in the next section.

3.4 Rebound effect calculation

The rebound effect is calculated to examine the success of the proposed efficiency program in reducing the energy demand. The rebound effect is calculated using Eq. (10) [28].

$$RE_t = 1 - \frac{AES_t}{PES_t} \tag{10}$$

Where RE_t illustrates the value of the rebound effect in each year, AES_t indicates the actual energy saving that is realized in each year, and PES_t is regarded as the expected value of energy savings based on engineering calculations. In economy-wide rebound effect calculations, the economy-wide expected value of energy-saving is calculated based on the expected value of energy savings in energy-intensive industries, as well as the share of energy-intensive industries in energy consumption (Eq. (11)).

$$PES_t = \alpha_t \times \sum_j \tau e_{j,t} \tag{11}$$

Where α indicates the share of energy consumption of the energy-intensive industries from national energy consumption and τe indicates the efficiency improvement of the energy-intensive industries.

4 Model Results

Based on environmental concerns, petroleum products in the industries of Iran have been substituted by natural gas to a large extent. The share of petroleum products in the energy consumption of industries in Iran has decreased from 38% in 2000 to 9% in 2019 [2, 29]. The vector of energy efficiency potentials in energy-intensive industries of Iran only contains solutions that decrease the demand for electricity and natural gas. Therefore, oil demand is not directly affected by the implementation of the energy efficiency program.

For 2019 which is the first period of the analysis, it is assumed that the government finance the energy efficiency solutions from the development budget. The amount of funds is set equal to 0.1% of the oil revenues of 2019. After that, the required funds are supplied from avoided subsidies.

Based on the supplied funds, the energy efficiency solutions are chosen in the model depending on their costs. Based on model results, some of the efficiency solutions which are selected in the first period of starting the program include hot air channel insulation and heat recovery from the chimney in the brick industry, the use of waste fuels for agglomeration (waste coal), adding automation system and process control in coking in the steel industry and the optimization of heat recovery in clinker cooling in the cement industry.

Table 1 shows the pathway of realizing energy efficiency potentials in energy-intensive industries. The results show that all efficiency enhancement solutions can be financed before 2026. The efficiency solutions in each year are chosen based on their energy-saving potential per unit of required investment and based on released funds from avoided subsidies in the previous year. After seven years, the viable predetermined energy efficiency solutions in energy-intensive industries are all implemented. This contributes to the cumulated amount of 12.7% electricity end-use efficiency improvement and 18.1% natural gas end-use efficiency improvement in these industries.

Leontief coefficients of the input/ output table in the CGE model ($ica_{a,c}$ in Eq.(2)) are updated in accordance with the improved energy efficiency and the subsequent amount of energy savings. Initially, in the baseline scenario the value of $ica^{Base}_{energy,a,t}$ (in Eq.(4)) for energy-intensive industries is 0.049 for electricity and 0.035 for natural gas. The seemingly low value of energy share in the production function of energy-intensive industries is due to the high energy subsidy to these sectors that results in a low share of energy cost in the total cost of production. After efficiency improvement the value of $ica^{EE}_{energy,a,t}$ (in Eq.(4)) for energy-intensive industries is reduced to 0.041 for electricity and 0.027 for natural gas. The price and income effects of these changes are propagated throughout the economy.

Over time, due to improved energy efficiency, the price of the outputs of energy-intensive industries gradually decreases. The price reduction relatively increases demand for the products of the energy-intensive industries. The relative price of the products in industries with a high share of intermediate inputs from energy-intensive industries (downstream industries), such as construction and machinery sectors, reduces over time. Therefore, improving efficiency in energy-intensive industries shifts the supply curve of downstream industries to the right and reduces the equilibrium price of outputs of those industries.

On the other side, improving energy efficiency in the energy-intensive industries reduces the energy demand of the industries. It puts downward pressure on energy prices. However, any decrease in energy price increases the energy demand of the household sector. Because the household sector has not been nominated for subsidy removal, improving energy efficiency in the industries increases energy demand in the household sector. This offsets some of the energy savings achieved in the industry sector. Results show that the aggregate effect of improving energy efficiency on total energy demand is still in favor of energy-saving. That means the rebound effect is less than one and there is no backfire effect.

Figure 3 illustrates the trend of changes in demand for electricity and natural gas, compared to the baseline scenario. The results of the model indicate that in the long run about 0.73% of total natural gas demand and 2.5% of total electricity demand are saved compared to the Baseline scenario.

The implementation of the proposed efficiency program leads to a 0.46% and 0.74% increase in gross domestic product and capital stock in the long term, respectively. Among industries, the energy-intensive industries, construction, and machinery sectors have the highest growth in the long term (0.9%, 0.7%, and 0.7% increase compared to the baseline scenario, respectively). The growth of the construction and machinery sector is due to their higher share of intermediate inputs from energy-intensive industries. Further, the electricity and natural gas sectors are the only sectors experiencing negative growth. The oil sector is almost not affected by the proposed energy efficiency program. Oil production increases by 0.01% due to the spurred economic growth.

The model results indicate that the implementation of the proposed efficiency program reduces emissions by about 25 million tons of CO_2 in 2030. This is the economy-wide effect of increasing the energy efficiency of energy-intensive industries and is calculated based on the average emission factors of natural gas and petroleum products. The amount of avoided emissions implies that Iran can reduce greenhouse gas emissions by more than 4% until 2030. This is enough to fulfill Iran's commitment to the Paris Agreement. The accumulated CO_2 emission reduction during the period under study is about 554 million tons of CO_2

The rebound effect of increasing the efficiency of electricity-consuming devices and natural gas-consuming devices is calculated according to Eq. (10-11). Figure 4 demonstrates the rebound value for the period under study for electricity and natural gas.

As shown, the value of the economy-wide rebound effect becomes negative. The negative value of rebound implies that the amount of actual energy saving is higher than its expected value. In other words, decreasing energy subsidies along with improving energy efficiency neutralizes the rebound effect. This is due to the induced changes in the sectoral composition of the production and changes in the relative prices and activity level of energy-intensive industries.

Mitigating the rebound alongside subsidy removal improves sustainability. According to Razmjoo and Sumper [30] economic and environmental sustainability can be calculated using indices including per capita consumption of commercial energies, Final energy intensity, and carbon intensity. Decreased consumption of natural gas and electricity reduces the per capita energy consumption and CO_2 emission. In addition, because the induced increase in GDP (0.46%) is less than natural gas and electricity demand reduction (0.73% and 2.5% respectively), the energy intensity also declines. This in turn improves both economic and environmental sustainability.

Synchronizing efficiency enhancement with increased energy prices prevents the deterioration of socio-economic conditions caused by rising energy prices. This is especially noteworthy when electricity price rises are to be implemented as part of electricity reforms. As discussed by Abdallah et al., [31] implementing energy reform to increase efficiency and market considerations generally requires upward adjustments in prices to provide for the required investments. This would have a negative impact on social sustainability. However, entangling price adjustment with efficiency improvement addresses some aspects of social concerns about sustainability.

5 Conclusion

The present study aims at investigating the economy-wide effects of increasing energy efficiency (in technical terms) based on a detailed representation of energy efficiency potentials. It provides a foundation that honors both engineering and economic principles. Efficiency potentials are based on viable previously studied efficiency potentials in the energy-intensive industries of Iran. The model can prioritize energy efficiency potentials based on their costs and benefits. The potentials are then fed into the general equilibrium model and the energy efficiency pathway and the yearly amount of subsidy removal is calculated. The prototype for increasing energy price is consistent with mitigating the rebound effect.

The present study emphasizes two points. First, from a methodological point of view, in calculating the rebound effect the amount of investment needed to improve the energy efficiency and its financial sources should be included in the model. The scarcity of investment funds and the impact of allocating a part of it for improving efficiency automatically reduces the calculated rebound effect in the model. The reason lies in the fact that using a scarce resource puts upward pressure on its price. Higher rates of return on capital mean higher production cost and this acts in the opposite of energy efficiency which lowers the production cost.

Second, from a policy-making point of view, applying policies that simultaneously target energy efficiency and energy subsidy can increase the speed of reducing energy consumption and emission. It should be noted that the implementation of the proposed efficiency program requires effective government assistance, which is especially highlighted in developing countries where there are multiple barriers to improving efficiency. The government, as a stimulus to improve efficiency, initiates a cycle that improves efficiency and reduces energy subsidies together. The government can borrow from national financial resources such as National Development Fund to finance efficiency solutions for the first year of the program. The loan can be repaid from the accrued benefits of the program.

At the time the prioritized efficiency solutions are all implemented, there will be no need for government to finance efficiency solutions. Yet, the energy conservation and energy price are higher than the base year. Thus, after some years the saved financial resources are not used to finance energy efficiency solutions and the loans can be repaid to the National Development Fund.

The proposed efficiency program has secondary benefits such as the boom in the work of energy service companies, leading to job creation and the promotion of the consumption culture, and the efficiency improvement in the community. In contrast to the normal condition in resource-rich countries where the employment and revenue are mainly created through energy extraction and consumption, the proposed efficiency program generates a force for creating revenue from reducing energy consumption and clean production.

The results of the model have indicated a long-term decrease in demand for natural gas and electricity (about 0.73% and 2.5% compared to the BAU scenario). The accumulated CO_2 emission reduction during the period under study has decreased by about 554 million tons of CO_2 compared to the baseline scenario. The calculation of the rebound effect has demonstrated the success of the proposed efficiency program in neutralizing the rebound and reducing energy consumption by more than the expected value in the long term.

The impact of applying mixed policy instruments on the employment and consumption culture can be the subject of further studies. Finally, the impact of the proposed efficiency program on the penetration of renewable energies and clean production can be considered for further research.

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Appendix A: List of selected energy efficiency opportunities

Table A1: Selected energy efficiency opportunities in six energy-intensive industries of Iran. [23]

Efficiency Solution	Cost of energy efficiency solution [million$/Ton of output]	Energy saving [PJ/Ton of output]
The furnace Insulation in the Brick industry	0.00019	0.17
Using Tunnel Dryer in Brick Industry	4.32	1
Automation system and process control in coke making in the Steel industry	0.092	0.042
Recycling heat from ashes in the blast furnace	13.12	0.925
optimization of heat recovery in the cooling system of clinker in the Cement industry	0.218	0.104
using waste heat in the process of peeling in the paper industry	0.231	0.545
Reducing the melting time in the furnace in the Glass industry	0.929	0.265
Preheating tunnel for preheating the material in the Aluminum industry	1.77	0.22

Table A2: the value of parameters α and β in the household demand function

	gamma (subsistence bundle, in 2011 Toman)		beta (share parameter)	
	urban households	rural households	urban households	rural households
Agriculture	13370	12239	0.08	0.13
Food industry	16123	5062	0.16	0.22
Cloth and paper	7195	2486	0.01	0.02
Chemical industry	11690	3930	0.06	0.10
Energy-intensive industries	8464	3685	0.00	0.01
Other industry	16183	4441	0.06	0.06
Electricity	4232	2948	0.01	0.01
Natural gas	3023	1965	0.03	0.02
Water	1008	492	0.01	0.01
Building	336	50	0.00	0.00
Services	25093	5179	0.51	0.35
Transportation	3602	1388	0.05	0.07
Public services	335	152	0.00	0.00

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