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Hoard or exploit? Intergenerational allocation of exhaustible natural resources

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Abstract

In this paper we develop a "general equilibrium" (GE) model for the allocation of exhaustible natural resources to examine the impact of different extraction scenarios on intergenerational economic welfare. We apply a stylized GE model to Israel's natural gas (NG) market to evaluate economic indicators resulting from NG-extraction scenarios: a **baseline scenario** based on current policy in the NG sector, a **conservative scenario** based on a lower extraction rate, and an **intensive scenario** based on faster extraction. We also examine the impact of various resource income-allocation strategies on intergenerational economic welfare through the mechanism of a "sovereign wealth fund" (SWF). The results indicate that a higher NG-extraction rate combined with an appropriate investment strategy for NG profits is preferable from an economic perspective to a conservative rate. Investment of the government take from the NG market in research and development (R&D) of renewable electricity productivity can sustainably increase economic welfare.

Keywords

Economic welfare, Energy, Exhaustible resource, General equilibrium model, Sovereign Wealth Fund (SWF), Natural Gas.

1. Introduction

Exhaustible natural resources (NR) are defined as natural materials that have an extremely slow growth rate relative to their rate of consumption, putting them at risk for complete depletion. Oil, coal, natural gas (NG), and metals are some examples of NR [1]. According to [2], the main features of an exhaustible resource are that its growth rate is nil and that it is nonrecyclable. Furthermore, it serves as essential input for production. Accordingly, decisions made today about exhaustible resource extraction have consequences for the welfare of both current and future generations [3-5].

Concern about limited and exhaustible resources is an age-old issue and was raised by Thomas Maltus in his classic book published in 1798. Maltus suggested that rapid population growth would exceed the carrying capacity of the land's limited natural resources [6]. This theory was later expanded to include the availability of other exhaustible resources, such as fossil fuels and mineral deposits. Nevertheless, Maltus's pessimistic prediction did not come to pass because, as economists suggest, resource scarcity can be forestalled by technological progress, changes in consumer preferences, and appropriate price signaling (see for example [7-9]).

Many questions have been raised regarding natural exhaustible resources. The basic questions addressed by researchers were: How should resource extraction be optimally allocated over time [7]? Can a market economy with exhaustible resources reach an optimal equilibrium [10]? What are the conditions needed to avoid a drop in the level of per capita consumption in the long run [3]? What are the necessary conditions for making the use of exhaustible resources compatible with sustainable development [9]? How are resources extracted over time in a market economy [11]? Is the market efficient at allocating the exhaustible resource [2]? What are the implications of resource exhaustibility in the context of economic growth [12]? What is the optimal pricing and taxation policy [13]?.

The management of an exhaustible resource has a temporal dimension and long-lasting effects. Decisions taken now regarding the management of such resources depend on price dynamics, speed of technological progress, and changes in tastes and preferences [14].

The problem of intergenerational equality looms large in natural resource and environmental planning, while sustainable development is essential for economic welfare and growth [14]. [15] showed that it is not necessarily the present generation that benefits most from a windfall of resources. The question of whether it is possible to maintain a non-declining per capita income has a long-lasting effect, emphasizing the importance of relying on objective methodology in the decision-making process. One of the basic arguments surrounding exhaustible resources concerns whether governments can influence intergenerational income distribution, justify governmental involvement, and know how to measure its outcomes [16]. In practice, the relationship between economic growth and the use of exhaustible natural resources must be a basic principle in formulating policies and making decisions with long-term impacts. This is especially important in the case of public resources that are not distributed effectively by market forces [16-17].

The discovery of exhaustible natural resources, especially those used to produce energy, can be a blessing for a country by easing the challenges of energy security and supply reliability. Yet history shows that this blessing in some cases may become a curse, when resource windfalls lower growth by crowding out traded sector production [18]. Therefore, there is a need for comprehensive analyses of the necessary policy governing these resources that will ensure long-term sustainable economic growth. Such a policy must delineate the rate of resource extraction and allocation across generations, the taxation scheme, and government revenues for utilizing the resource's value. Policy setting is essential for countries in which exhaustible resources have been recently discovered.

Experience in countries such as Norway, which have succeeded in utilizing oil revenues to promote economic growth, experience proves that it is mainly management of the natural resource revenues that leads either to economic growth or to resource curse [19]. Therefore, exhaustible natural resource management is essentially a matter of policy, and proper management can lead to economic growth. Setting a management strategy that relies on objective and comprehensive analyses in considering the economic impacts of exhaustible resources is essential for efficient management of a nation's wealth.

In Israel, 900 billion cubic meters (BCM) of NG were discovered in 2010. After traditionally relying on coal and oil imports, Israel has become self-sufficient in its energy consumption, using domestic NG as the main source of power generation since 2012. As in many other countries, Israel encouraged the transition to NG as a primary energy source, emphasizing the advantages for the consumer, the economy and the environment. Yet heated public debate arose around the question of whether to maintain a slow extraction rate to preserve the reserves for domestic use or to accelerate the extraction by allowing exports.

In the current research we develop a novel approach to analyze decisions regarding the extraction path of non-renewable resources, and particularly NG. We consider the impact of the immediate use of these resources versus a lower level of exploitation over time in the Israeli market. The case of Israel, a country with a small open economy that was recently endowed with a NG windfall, can serve as an example for other countries, especially those with small open economies that have discovered exhaustible natural resources. The proposed model can be adapted to case-specific characteristics.

The current study can be used to draw up policies and to identify the effects on macroeconomic indicators. Moreover, it can serve as a tool to verify whether policies and regulations regarding exhaustible resources are valid, suitable and adequate for the goals and objectives of this policy and regulation.

In this paper, we establish an economic framework addressing the main questions that have arisen regarding the preferred management strategy for the extraction of exhaustible resources. We determine a mechanism for allocating the resource between current and future generations and investigate the impact of resource-revenue allocation on economic welfare using GE methodology. Specifically, we determine an intergenerational policy of allocating exhaustible natural resources and calculate the impact of different extraction scenarios on the economic welfare of society. We then apply the model to the Israeli NG market to evaluate economic indicators emerging from different NG-extraction scenarios: a **baseline scenario** based on the current policy in the Israeli NG sector, a **conservative scenario** based on a lower extraction rate, and an **intensive scenario** based on a more aggressive extraction rate. We determine a mechanism for allocating exhaustible resources between current and future generations, using a sovereign wealth fund (SWF) as a tool for transferring welfare between the generations. Current research in the NG field is conducted using theoretical models of economic growth, and it examines the impact of resource income-allocation strategies. To the best of our knowledge, this has never been done for the Israeli NG sector.

The paper continues as following: Section 2 describes the methodological approach and the model specifications. Section 3 provides background for the Israeli NG sector. Section 4 describes the NG extraction scenarios, including the data sources. Section 5 provides simulation results for the different NG extraction scenarios in the Israeli market. The last section concludes and provides policy recommendations.

2. Model Specification

In this section we propose a simple macroeconomic growth model to evaluate different management scenarios and their welfare effects. We set out a general model of resource extraction and use in which the key economic players are explicitly represented. We set up the individual, resource-extraction firm and producer problems and derive the necessary conditions for equilibrium. Starting with the classic model proposed by [20] for intertemporal choice, we added an explicit definition of the consumer problem from [5]. We modeled the government take based on Israeli regulations, using SWF as a mechanism for transferring income to the public, as in [21]. The electricity producers problem is defined based on [22]. These models were adjusted in order to comply with the regulations in the Israeli NG sector.

The economy in the current model consists of the exhaustible resource-extraction sector, the electricity-generation sector, the government, and two generations of consumers. In the following section, we describe the different sectors of the economy. In this paper we do not seek the optimal path of NG extraction to achieve equilibrium in the model. Rather, we compare three different scenarios of NG extraction, as described in Section 5.

We consider a two-sector economy (the exhaustible resource-extraction sector and the electricity sector). We also consider NG and renewable energy resources as the only inputs used for power generation. The justification for this approach is in line with [23], who emphasized that the essential features regarding exhaustible natural resources are more conveniently isolated when they are the only inputs into the model. This assumption reflects the Israeli electricity sector in which the main expenses are for fuel, comprising almost 40% [24] We also assume that NG is used only for power generation, as in the Israeli energy economy 80% of NG is used for electricity. Furthermore, the NG reserves discovered in Israel are very significant relative to the size of the Israeli economy and are expected generate a comparative advantage. These fields provide an opportunity for Israel, considered an "energy island"[1], to reduce its energy dependency [25-28] and are expected to provide a solution to the electrification of the country’s energy market.

[1] In light of Israel’s disconnected energy infrastructure system with neighboring states.

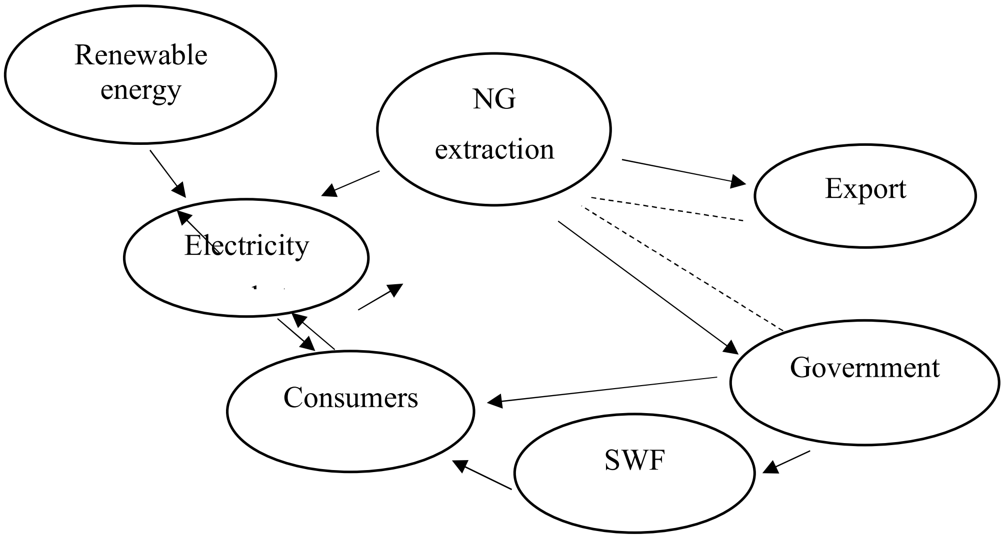

Figure 1. Diagram of the modeled economy.

Figure 1 graphically depicts the sectors in the economy covered by the model and the relationships between them. The dashed lines in Figure 1 depict the exported amounts of NG that are not counted in calculating consumers' utility since we only examine the welfare of domestic citizens. However, the taxes paid on these amounts are included in the model, since they are paid to the local government and transferred to Israeli consumers and to the SWF.

The exhaustible resource-extraction sector includes the NG-extraction firms that extract and transmit the NG to the electricity producers and to export. The directions of the arrows in Figure 1 represent the directions of the transactions; thus, the extraction firms pay taxes to the government, which serves as regulator and public trustee. The government transfers a share of the taxation income directly to the consumers through the government budget, while the rest is transferred to the SWF. The SWF is invested in assets outside the country, and the rate of return on these investments is also transferred to the consumers. The consumers use this money to buy electricity, which we assume is the only final good in this economy.

In our model, we measure welfare by focusing on consumer utility, SWF value and NG-extraction firm profits (assuming that these profits belong only to the firms and are not transferred to individuals). On the other hand, since the electricity-generation firms are owned by individuals, their profits are included in the consumer utility. Next, we provide a mathematical description of the model.

2.1 Exhaustible natural resource-extraction sector

We assume that the country discovered a certain amount of an exhaustible natural resource, NG, and that it is the country's responsibility to distribute the wealth between current and future generations. Nevertheless, in the Israeli market a small number of firms have a license for NG extraction, and they act as an oligopoly. For simplicity, we develop the model under perfect competition, but one can easily analyze the model under monopoly or oligopoly.

Suppose natural resource-extraction firms choose the amount of resource to be extracted in every period E_t. This is assumed because the economy is initially endowed with an exhaustible natural resource, NG, and in each period the total stock of the resource is determined by the past resource stock *minus* the current resource extraction E_t, such that:

$$NG_{t+1} = NG_t - E_t \qquad (1.1)$$
$$E_t \le NG_t \quad \forall t$$

E_t is either consumed in the domestic market (E_N) to produce good X_t or exported (E_X), such that:

$$E_{Nt} + E_{Xt} = E_t \qquad (1.2)$$

Assuming competitive markets, the natural resource price P_t^{NG} is equal in both markets.

Extraction firms maximize their profits in each period as follows:

$$Max \quad \Pi(E_t) = P_t^{NG} * E_t - TC(E_t) \qquad (1.3)$$

The parameter *TC* refers to the total cost, including the extraction costs, referred to as *F*, that are fixed and determined by the extraction firms. The government share of the resource wealth includes income tax and royalties directly transferred to the government budget (referred to as dt_t) and a levy which is transferred to the SWF (S_{it}), such that in Israeli regulation, we assume that *TC* consists of:

$$TC = F + dt_t(E_t) + S_t(E_t) + EC_t(E_t) \qquad (1.4)$$

F represents the fixed costs.

The variable costs depend on the extracted NG amount and include: $dt_t(E_t)$ direct transfers to the government, $S_t(E_t)$ transfers to the SWF $EC_t(E_t)$ variable extraction costs.

From first-order conditions, we obtain:

$$P_t^{NG} = \frac{\partial TC(E_t)}{\partial E_t} \qquad (1.5)$$

2.2 Government transfers

Here we assume that the extraction firms transfer a share of the NG income to the government, G, based on local regulations and in accordance with Israeli regulation.

We refer to E_t as the amount of extracted NG at period *t*, and assume that this amount is used either for electricity production on the domestic market or for export (see equation 1.2).

In the current model, we assume that the government transfers some portion of its payments directly to the individual through its yearly budget and that the other portion is transferred to a SWF, $SWF_t(E_t)$, while $S_t(E_t)$ is an amount that is periodically transferred from extraction firms to the government, such that:

$$R_t(E_t) = dt_t(E_t) + \varepsilon SWF_t(E_t) \qquad (1.6)$$

where:

$R_t(E_t)$ is the periodic governmental transfer to individuals at time *t*, $dt_t(E_t)$ denotes the direct transfers to the current generation through the government budget, which are finite and limited to the field's lifetime, such that: $\lim_{t\to\infty} dt_t = 0$. ε is the rate of return on the SWF investment. The fund is invested in accordance with national regulations[2] in Israel.

$$SWF_{t+1}(E_{t+1}) = SWF_t(E_t) + S_t(E_t) \qquad (1.7)$$

$dt_t(E_t)$ and $S_t(E_t)$ are functions of *E*, indicating that government transfers depend on the amounts of gas extracted in every period. These payments are transferred directly from the NG-extraction firms to the government and can be viewed as taxes.

$$\sum_{t=1}^{\infty}\left(\frac{1}{(1+r)}\right)^{t-1} G_t(E_t) = \sum_{t=1}^{\infty}\left(\frac{1}{(1+r)}\right)^{t-1} S_t(E_t) + \sum_{t=1}^{\infty}\left(\frac{1}{(1+r)}\right)^{t-1} dt_t(E_t) \qquad (1.8)$$

Equation 1.8 implies that the present values of current and future transfers to individuals (the right-hand side of the equation) are equal to the value of the resource wealth, *G*, which represents the government's share of the total wealth generated from the extracted exhaustible resource. The transfer mechanism is similar to that in [21], except that in our model, government transfers consist of two

[2] According to the Israeli Petroleum Profits Tax Law [29], the SWF's assets will be invested outside of Israel, and its goal is to manage the state's income from oil profits via a long-term economic perspective. The purpose is to allocate the fruits of this fund annually to social, economic and educational goals, and to assist in handling unusual events, including environmental events, with negative impacts on the Israeli economy.

components: direct transfers and transfers to individuals through the SWF (indirect), in accordance with Israeli regulation in the NG sector.

2.3 Electricity consumers

In terms of consumption, total domestic supply is assumed to meet demand exactly (market clearing). In the current study, we follow the theory of rational intertemporal choice [20]. We assume that an individual's consumption is driven by maximization of a constant elasticity of intertemporal substitution function (IES), as in [5], subject to a budget constraint. One basic assumption of this function is that individuals maximize the sum of all their future utilities. The intertemporal elasticity of substitution shows how strongly households substitute their current consumption against future consumption in response to a change in the real interest rate across the economy. This theoretical framework is based on the utility specification that is widely used in structural macroeconomic models and life-cycle models [30].

In the current study, we analyze the NG sector in Israel and refer to electricity as a final product in the economy. NG can also be used in the industrial and transportation sectors. Yet for the sake of simplicity, we assume that NG is used only in the electricity sector.

At a given time *t*, individuals live for two periods. In the current model, we assume there is no population growth. Thus, we can normalize the number of consumers to one in every period, such that in every period there are two individuals, one young and one old. Each individual receives a flow of government transfers, R_t, from exhaustible resource revenues. Government transfers in each period are assumed to be distributed equally between the two living generations. The individual maximizes his or her intertemporal utility U by choosing C_t^y, the consumption during the first period when he or she is young, and C_{t+1}^o, the present value of the consumption during the second period when he or she gets old, under the budget constraint. We also assume that individuals own electricity-generation companies and use their producer profits Π_t for electricity consumption. Profits are collected only by the younger generation in each period.

Let $\beta \geq 0$ be the individual's time preference, as the time discount factor is a measure of the subjective time preference (consumption today vs. consumption in the next period). As in [5], we assume constant elasticity of the intertemporal substitution function[3].

[3] In economics with balance-growth paths, we need to assume consumer preferences with constant elasticity of intertemporal substitution, see [31-32].

$$Max \qquad U = \ln C_t^y + \beta \ln C_{t+1}^o \qquad (1.9)$$

$$S.t \qquad C_t^y + \frac{C_{t+1}^o}{1+r} = \Pi_t + \frac{R_t}{2} + \frac{R_{t+1}}{2(1+r)} \qquad (1.10)$$

The left-hand side of the budget constraint represents the present value of an individual's lifetime consumption. The right-hand side is the value of the individual's lifetime income, which consists of the producers' profits from the electricity sector, Π_t, assuming as in Fisher [20] that the production firms are owned by young individuals, the producers' profits are as defined below, and the total governmental transfers are R_t and R_{t+1}. We assume that the total transfers in every period R_t are distributed equally among living individuals in that period. Since every period includes two different individuals representing two different generations, the government transfers are equally divided between them. The discount rate, *r*, is considered exogenous by individual. As in [21], we assume that individuals are forward-looking, so they have knowledge of the total value of all the transfers they will receive during their lifetimes.

The Lagrangian

$$\ln C_t^y + \beta \ln C_{t+1}^o - \lambda[C_t^y + \frac{C_{t+1}^o}{1+r} - \Pi_t - \frac{R_t}{2} - \frac{R_{t+1}}{2(1+r)}] = 0 \qquad (1.11)$$

F.O.C

$$\frac{\partial U}{\partial C_t^y} = \frac{1}{C_t^y} - \lambda = 0 \longrightarrow \frac{1}{C_t^y} = \lambda \quad (i)$$

$$\frac{\partial U}{\partial C_{t+1}^o} = \frac{\beta}{C_{t+1}^o} - \frac{\lambda}{1+r} = 0 \longrightarrow \frac{\beta}{C_{t+1}^o}(1+r) = \lambda \quad (ii)$$

$$\frac{\partial U}{\partial \lambda} = C_t^y + \frac{C_{t+1}^o}{1+r} - \Pi_t - \frac{R_t}{2} - \frac{R_{t+1}}{2(1+r)} = 0 \quad \text{(iii)}$$

$(i)+(ii)$: $C_{t+1}^o = \beta(1+r)C_t^y$

From this equations and equation (iii) we get:

$$C_t^y + \beta C_t^y = \Pi_t + \frac{R_t}{2} + \frac{R_{t+1}}{2(1+r)}$$

$$C_t^y = \frac{1}{1+\beta}\left(\Pi_t + \frac{R_t}{2} + \frac{R_{t+1}}{2(1+r)}\right) \qquad (1.12)$$

$$C_{t+1}^o = \frac{\beta(1+r)}{1+\beta}\left(\Pi_t + \frac{R_t}{2} + \frac{R_{t+1}}{2(1+r)}\right) \qquad (1.13)$$

Functions (1.12) and (1.13) represent the consumption of every individual in each period. The consumption functions of the representative individual are characterized by constant budget shares of total discounted lifetime income, which, in turn, are functions of the total income generated by output production and government transfers to the individual, the real-world interest rate and the subjective discount rate.

2.4 Electricity producers

In line with [22], production is defined as a normalized constant elasticity of substitution (CES) function. CES functions make up a key part of energy economy models and are one of the most common aggregate production functions [33]. In addition, GE models are an important application of empirical CES study results [34]. GE models are the most popular models and are commonly CES-based [33, 35-36].

We assume that competitive firms produce a homogeneous good X_t using exhaustible resource E_t, and renewable resource Z_t, with all other factors in the economy fixed. Since we are interested in examining the effect of NG on the economy, we normalize all other factors to unity.

We assume that the exhaustible resource can be used in the domestic market for production: E_{Nt} is the amount used for production of X_t . The exhaustible resource can also be used for export. While E_{Xt} is the total export amount at time *t,* we assume that any amount slated for export will be bought on the international market (equation 1.2).

Electricity production (X_t) is given by:

$$X_t = (\mu^E E_{Nt}{}^{\alpha} + \mu^Z Z_t{}^{\alpha})^{1/\alpha} \qquad \alpha = \frac{\sigma - 1}{\sigma},\ \mu^i \geq 0 \qquad (1.14)$$

where $\alpha = \frac{\sigma - 1}{\sigma}$ represents the substitution parameter that measures the percentage change in the ratio of two inputs in response to a percentage change in their prices. The function shows that the elasticity of substitution is a constant whose magnitude depends on the value of the parameter σ[4]. Here, Z_t represents the backstop technology, i.e., an energy source other than NG (such as renewable energy).

[4] If $\alpha = 1$, we have the linear or perfect substitution function; if $\alpha = 0$, we have the Cobb–Douglas production function, and if $\alpha = -\infty$, we have the Leontief production function.

μ^i represents the productivity factor of input *I* (i.e., NG and renewables). Firms are interested in maximizing profits by choosing the amount of input that will be utilized in the production process:

$$Max \quad \Pi_t = (\mu^E E_{Nt}{}^{\alpha} + \mu^Z Z_t{}^{\alpha})^{1/\alpha} * P_t{}^E - P_t{}^{NG} E_{Nt} - P_t{}^z Z_t \qquad (1.15)$$

where, $P_t{}^{NG}$ is the price of the exhaustible resource (NG), $P_t{}^z$ is the price of the backstop technology, and $P_t{}^E$ is the output price (i.e., price of electricity).

The first-order conditions are:

(i) $$\frac{\partial \Pi_t}{\partial E_{Nt}} = 0: \ \mu^E E_{Nt}^{\alpha-1} \ (\mu^E E_{Nt}^{\alpha} + \mu^Z Z_t^{\alpha})^{1/\alpha-1} \ P_t^E = P_t^{NG}$$

(ii) $$\frac{\partial \Pi_t}{\partial Z_t} = 0: \ \mu^Z Z_t^{\alpha-1} (\mu^E E_{Nt}^{\alpha} + \mu^Z Z_t^{\alpha})^{1/\alpha-1} \ P_t^E = P_t^Z$$

$$(ii)/(i): \ \frac{\mu^E}{\mu^Z} \frac{E_{Nt}^{\alpha-1}}{Z_t^{\alpha-1}} = \frac{P_t^Z}{P_t^{NG}} \qquad (1.16)$$

2.5 RENEWABLE ENERGY SECTOR

We assume that the price of renewable energy sources is equal to the marginal cost of production and that there are no fixed costs or taxes in this sector, so that revenue equals costs and firms have normal profits only. We also assume that renewable energy is used by firms only for power generation. These firms are also owned by young consumers.

2.6 EQUILIBRIUM

Market clearing conditions in this class of models refer to the supply of a commodity that must balance the demand by consumers at equilibrium prices and activity levels.

We assume that the only source of government income is the taxes on the exhaustible resource. When the exhaustible resource is totally depleted, the economic growth is derived by the rate of return on the SWF's investment.

Note that X_t (i.e., electricity) is a nontraded good, meaning that it can be produced and consumed only in the domestic market. We also assume that:

$$C_t = X_t \qquad (1.17)$$

The demand side is the sum of demand from the younger (equation 1.12) and older (equation 1.13[5]) generations, such that:

$$C_t = C_t^y + C_t^o = \frac{1}{1+\beta}[\Pi_t + \frac{R_t}{2} + \frac{R_{t+1}}{2(1+r)}] + (1+r)\frac{\beta}{1+\beta}[\Pi_{t-1} + \frac{R_{t-1}}{2} + \frac{R_t}{2(1+r)}] \quad (1.18)$$

The supply side is given by equation 1.14. That equation and equation 1.18 yield:

$$(\mu^E E_{Nt}{}^{\alpha} + \mu^Z Z_t^{\alpha})^{1/\alpha} = \left\{ \begin{array}{l} \frac{1}{1+\beta}[(P_t^E(\mu^E E_{Nt}{}^{\alpha} + \mu^Z Z_t^{\alpha})^{1/\alpha} - P_t^{NG} E_{Nt} - P_t^Z Z_t) + \frac{R_t}{2} + \frac{R_{t+1}}{2(1+r)}] + \\ (1+r)\frac{\beta}{1+\beta}[(P_{t-1}^E(\mu^E E_{Nt-1}{}^{\alpha} + \mu^Z Z_{t-1}{}^{\alpha})^{1/\alpha} - P_{t-1}^{NG} E_{Nt-1} - P_{t-1}^Z Z_{t-1}) + \frac{R_{t-1}}{2} + \frac{R_t}{2(1+r)}] \end{array} \right\} / P_t^E \quad (1.19)$$

To solve this equation, we use the "generalized reduced gradient method" to seek the optimal Z_t to solve the equation:

$$(\mu^E E_{Nt}{}^{\alpha} + \mu^Z Z_t^{\alpha})^{1/\alpha} = \left\{ \begin{array}{l} \frac{1}{1+\beta}[(P_t^E(\mu^E E_{Nt}{}^{\alpha} + \mu^Z Z_t^{\alpha})^{1/\alpha} - P_t^{NG} E_{Nt} - P_t^Z Z_t) + \frac{R_t}{2} + \frac{R_{t+1}}{2(1+r)}] + \\ (1+r)\frac{\beta}{1+\beta}[(P_{t-1}^E(\mu^E E_{Nt-1}{}^{\alpha} + \mu^Z Z_{t-1}{}^{\alpha})^{1/\alpha} - P_{t-1}^{NG} E_{Nt-1} - P_{t-1}^Z Z_{t-1}) + \frac{R_{t-1}}{2} + \frac{R_t}{2(1+r)}] \end{array} \right\} / P_t^E \quad (1.20)$$

For the data assumptions and sources of the other variables (E_{Nt}, R_t, P_t^E, P_t^{NG}, P_t^Z) and the constants (γ, μ^E, μ^Z, α, r, β), see Table 13.

This method considers the gradient or slope of the objective function as a change in input values (or decision variables) and determines that an optimum solution has been reached when the partial derivatives equal zero. In this case, we look for a solution to the problem:

$$\left[\begin{array}{l} (\mu^E E_{Nt}{}^{\alpha} + \mu^Z Z_t^{\alpha})^{1/\alpha} * P_t^E - \frac{1}{1+\beta}[(P_t^E(\mu^E E_{Nt}{}^{\alpha} + \mu^Z Z_t^{\alpha})^{1/\alpha} - P_t^{NG} E_{Nt} - P_t^Z Z_t) + \frac{R_t}{2} + \frac{R_{t+1}}{2(1+r)}] + \\ (1+r)\frac{\beta}{1+\beta}[(P_{t-1}^E(\mu^E E_{Nt-1}{}^{\alpha} + \mu^Z Z_{t-1}{}^{\alpha})^{1/\alpha} - P_{t-1}^{NG} E_{Nt-1} - P_{t-1}^Z Z_{t-1}) + \frac{R_{t-1}}{2} + \frac{R_t}{2(1+r)}] \end{array} \right]^2 = 0 \quad (1.21)$$

We begin by assuming some data for the variable Z_t and minimize the distance between our prediction and the actual solution of equation 1.20 based on the actual data.

[5] Note that equation 1.13 is expressed in time (t+1). To sum the equations, equation 1.13 should be expressed in time t such that: $C_t^o = (1+r)\frac{\beta}{1+\beta}\left(\Pi_{t-1} + \frac{R_{t-1}}{2} + \frac{R_t}{2(1+r)}\right)$.

3. Natural gas in Israel

Until the early 2000s, Israel was considered a resource-deprived country, especially regarding fossil fuels [37]. Israel traditionally relied on coal and oil imports, but in the last two decades began diversifying its energy sources through the use of NG. Israel's first commercially recoverable discovery of fossil fuel was in 1999, when NG was discovered at the Yam Tetis. A decade later, major discoveries were made at the Tamar and Leviathan offshore structures. Together the proven reserves reach about 900 billion cubic meters (BCM), while annual domestic consumption is about 12 BCM. Major public investments in the transmission infrastructure are projected so as to double the demand.

Policymakers and the public in Israel have raised many questions regarding the optimal policy for developing and managing the NG discoveries. Such questions have been tackled by other countries as well. The basic question refers to whether to exploit the gas or to hoard it. Other questions are related to government management of its share of revenues, the optimal sector structure, and export strategy. Deciding what proportion of the NG reserves should be preserved for domestic needs and how much should be exported is a particularly complex issue. On the one hand, NG exports are expected to enrich the government's take, which could then be invested in channels that can lead to economic growth. For example, investments in promoting R&D in renewable energies to increase technological efficiency, improve storage technologies and the like can in the long run provide a substitute for NG. On the other hand, the Israeli economy can enjoy the benefits of transitioning to NG in terms of energy security and cleaner (than coal) power generation by maintaining a large reserve of gas, which will serve as a stimulus for the transition.

Hence, comprehensive analyses are needed to determine the best policy for these resources that will ensure long-term sustainable economic growth. Such a policy must delineate the rate of resource extraction and allocation among generations, the taxation scheme, and government revenues to utilize the resource's value. A detailed policy analysis is essential for countries in which exhaustible resources have recently been discovered, such as Israel.

4. Extraction Scenarios

In this section, we provide a numerical simulation of the model for the Israeli NG sector across three different NG-extraction scenarios. Following [21], we define one period as 25 years, starting from 2015. In every period, two generations are present. The model is applied for three periods.

When applying the model, we use actual market data for the years 2014–2017. In the baseline scenario, the data for the following years (2018–2065) are based on the financial statements of NG-extraction firms in Israel as of 30 December 2017.

The baseline scenario is based on actual Israeli market regulation, which allows export of 40% of the total NG amounts. In this scenario, the NG will be completely depleted by 2065, i.e., in the second period of our model, which means that three generations[6] will benefit directly from the NG windfall.

The conservative scenario assumes a lower extraction rate, as the demand for NG originates solely from domestic use. This scenario simulates the public desire to preserve the NG solely for domestic uses in accordance with "strong sustainability criteria" that call for always keeping a minimum stock of reserves for future generations [38]. Therefore, no export is assumed. In this scenario, the NG is projected to be depleted by 2090 while suppling input for electricity production for five generations[7].

The intensive scenario assumes a higher extraction rate due to high demand in both domestic and export markets. Only the generations in the first period (two generations) can use NG for electricity generation until 2040. We assume that any amount slated for export will be bought on the international market. We also assume that NG-extraction firms pay the same share of taxes[8] in the three scenarios. Table 1 summarizes the data assumptions and sources.

[6] Note that in every period, two generations are alive: one young and one old. The young people from the first period will become the old people in the second period, and a new generation will be born, making three generations in total.
[7] In the three periods (2015–2040, 2041–2066, 2067–2090), there are five generations: We begin with the young and old generations in the first period. The young generation from the first period will become the old generation in the second period, and a new generation is born. In the third period, the young generation in the second period becomes the old generation, and a new generation is born.
[8] Adjusted to the extracted amount of NG.

Table 1. Data assumptions and sources across the three scenarios.

Assumptions	Baseline scenario	Conservative scenario	Intensive scenario
Export	Export of 9 BCM from 2020 to 2045, 5 BCM until 2059, and 2 BCM until field depletion in 2065, calculated based on [39]	No export	Export of 20.24 BCM from 2020–2040. In this scenario, we assume that domestic NG use is equal to that in the baseline scenario. The excess amount of NG is destined for export and is distributed equally across the period 2020 to 2040.
Depletion	Tamar projected depletion by 2050. The other fields supply NG until 2065.	The NG will be depleted by 2090, calculated based [39]. Tamar field will be depleted by 2050, calculated based on [39]NG-extraction amounts are similar to the baseline scenario for 2015–2065. Thereafter, we assume the amounts are distributed equally across the years.	All NG reserves are depleted by 2040. NG-extraction amounts are similar to the baseline scenario for the years 2015–2040 in the domestic market. The rest is exported.
Financial data	Data on annual NG extraction, firm incomes, costs, royalties, government share of royalties, levy, income taxes, and	Data on firm incomes and levies are similar to the baseline scenario until 2050. For 2051–2090, the data equal the average over the 5 years before the specific year; for example, income tax in 2051 equals	Data on annual NG extraction, firm incomes, costs, royalties, government share of royalties, levy, income taxes, and corporate taxes are based on [39].

<table>
<tr><td></td><td>corporate taxes are based on [39].</td><td>average annual income tax for 2044–2049.</td><td></td></tr>
<tr><td>Levy</td><td colspan="3">The levy is imposed on profits derived from the sale of NG pursuant to the [29]. The levy follows a progressive R-Factor-based tax[9] starting at 20% and increasing to about 45%. The government take from the levy is transferred to the SWF.</td></tr>
<tr><td>Corporate tax</td><td colspan="3">10% corporate tax in accordance with [29, 40]. The income taxes are transferred to the government budget.</td></tr>
<tr><td>Royalties</td><td colspan="3">Royalties of 24% of total cash flow; the government share of royalties is 11.5%, in accordance with the Sheshinski Committee [41] and [29]. The royalties are also transferred to the government budget.</td></tr>
<tr><td>Rate of return on SWF Investment (Same for all the scenarios)</td><td colspan="3">3% rate of return on SWF investment, based on [42], who found that rates of return on investments vary between 1% and 5%. In the benchmark scenario, we assumed 3% and then we conducted a sensitivity analysis to see how changing this assumption might change the results.</td></tr>
<tr><td>Transfers to individuals (Same for all the scenarios)</td><td colspan="3">The government transfers 3.5% of the SWF accumulated capital to the public between 2020 and 2034; in the following years, the government transfers an amount equal to the average rate of return for the previous 10 years multiplied by the accumulated capital, in accordance with the SWF Law of 2014.

3% rate of return on SWF investment.</td></tr>
</table>

Figure 2 shows the amount of exported NG in the different scenarios. We assume no export in the conservative scenario. We further assume that 40% of the total NG amounts will be used for export in the baseline scenario, whereas a higher rate of export will be used in the intensive scenario. These amounts depend on the NG-depletion rate, such that the export amounts are null when the total amount of NG is depleted.

[9] A complex formula considering the ratio between accumulated income and accumulated investments.

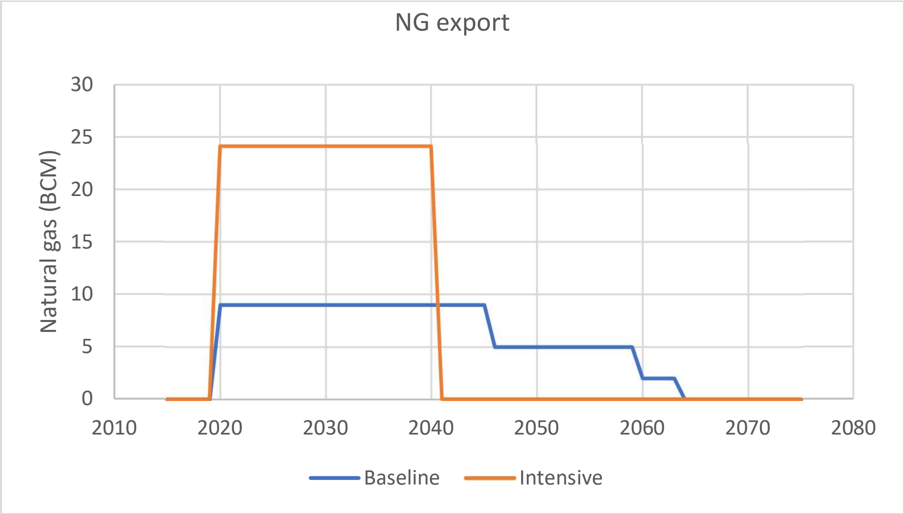

Figure 2. NG export amounts for the baseline and intensive scenarios.

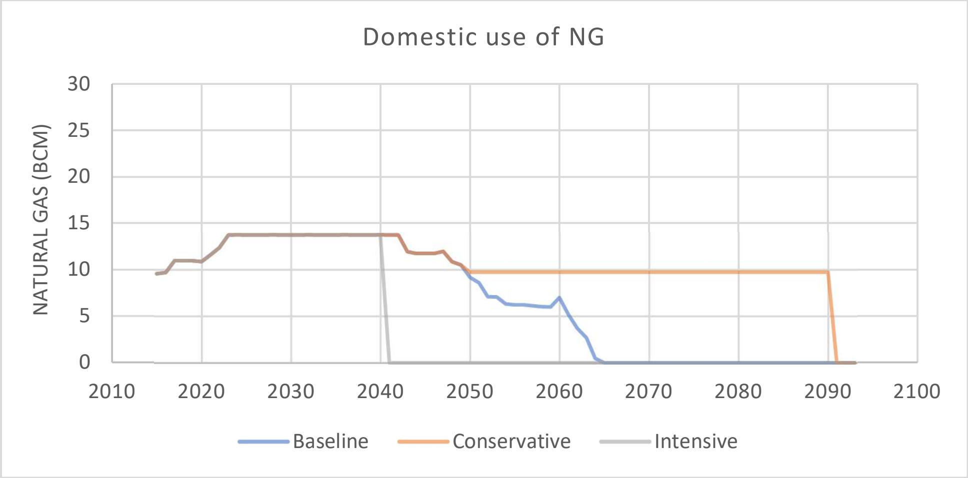

Figure 3. Domestic use of NG for electricity generation under the three scenarios.

Figure 2 shows that in the first period, NG usage is higher under the intensive scenario than under the baseline and conservative scenarios, and it reaches zero when the total gas amounts are depleted in 2040. In the baseline scenario, the domestic use of NG is less than in the conservative scenario due to the export amounts under the baseline scenario. However, the total extracted amount over the resource lifetime in the baseline scenario is equal to that in the conservative and intensive scenarios (850 BCM).

5. Results

5.1 Simulation results

Table 2 describes the data and sources for the model parameters:

Table 2. Parameter values and sources in the three scenarios.

Parameter	**Description**	**Data source**	**Range for sensitivity analysis**
$P_t^{NG} = 5.7\$ / MMBTU$	Cost of electricity generation by NG	[42]	\$4.5–6.7 /MMBTU
$P_t^{Z} = 0.0625\$ / kWh$	Cost of electricity generation by renewable energy	[42]	
$P_t^{E} = 0.14\$ / MMBTU$	Electricity tariff	[43]	
$\alpha = 0.6$ [10]	The substitution parameter measures the percent change in the ratio of two inputs used in response to a percent change in their prices	[44]	
$\beta = 0.015$	Individuals' subjective discount rate	[45-46]	0-0.045
$r = 2.5\%$	Annual discount rate	[40, 47]	1.5%–4.5%
$\mu^E = 60\%$	Productivity factor of NG	[48]	

[10] [44] examined the role of substitution from traditional to modern energy using a constant elasticity of substitution production function (SEC). According to the authors, as the share of modern fuels is initially very small while other fuels (coal and firewood in the stated model) can often be used for the same applications, it is likely that the substitution factor is higher than 1, so that neither fuel is essential. The authors estimated this factor to be about 4.4. In our model, we assume $\sigma = 2.5$ i.e. $\alpha = 0.6$. This value reflects high flexibility, meaning that NG can be easily substituted by renewable energy and vice versa.

$\mu^Z = 20\%$	Productivity factor of renewable energy sources	[43]	See extension 1 in Section 5.3

Figure 3 depicts the NG-extraction firm profits. In the first period profits are higher for the intensive scenario than for the baseline and conservative scenarios. In the second period profits are higher in the conservative scenario. The decline in profits is due to depletion of the NG fields. In the intensive scenario, the deposits will be depleted by 2040. In the baseline scenario, they will be depleted by 2065, and in the conservative scenario, by 2090.

Figure 3 about here

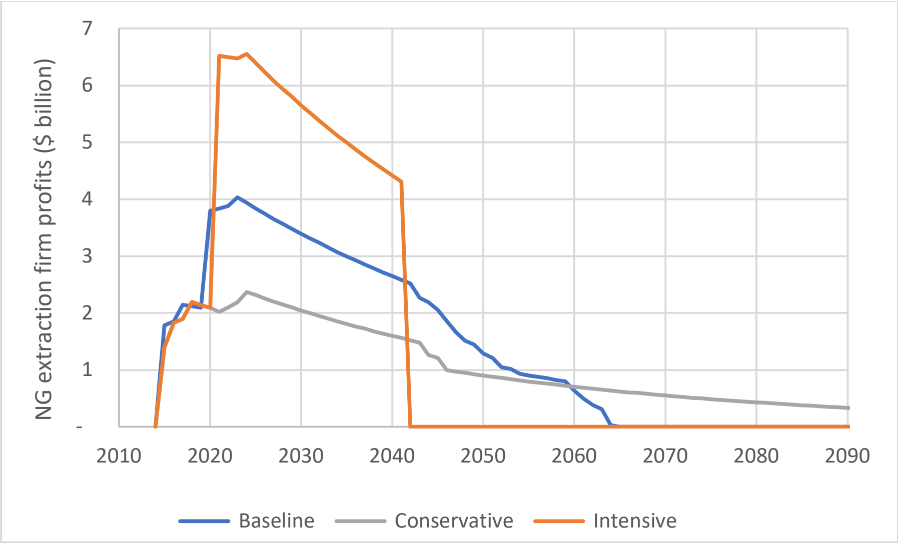

Figure 3**.** NG-extraction firm profits under the three scenarios.

Government transfers refer to the implementation of an income transfer policy, as defined in equation 1.7, with respect to Israeli regulation regarding NG wealth distribution. These transfers depend on NG-extraction amounts and NG prices. Table 3 describes the government take during the lifetimes of the fields under the different scenarios. The government take includes income tax, royalties and levy paid by the NG-extraction firms.

Table 3. Government take during the lifetime of the NG fields in the different scenarios, in 2018 prices.

	Baseline	**Intensive**	**Conservative**
Period	2015-2065	2015-2040	2015-2090
Total income ($ billion)	62.55	72.38	44.88

The calculations in Table 3 are shown in present values, at a 2.5% rate, following the [40] and [47]. They include the periodic government income without the SWF accumulation. As can be seen in the table, the government income in the intensive scenario is higher than in the conservative and baseline scenarios. The government income in the first period will be higher in the intensive scenario than in the baseline and conservative scenarios due to higher NG extracted amounts and will decrease to 0 at a higher rate when the NG is totally depleted.

Figure 4 describes the SWF accumulation. It shows the aggregate level of the SWF at the end of every year *t*, starting in 2020, the year in which the NG-extraction firms are expected to start paying levy.

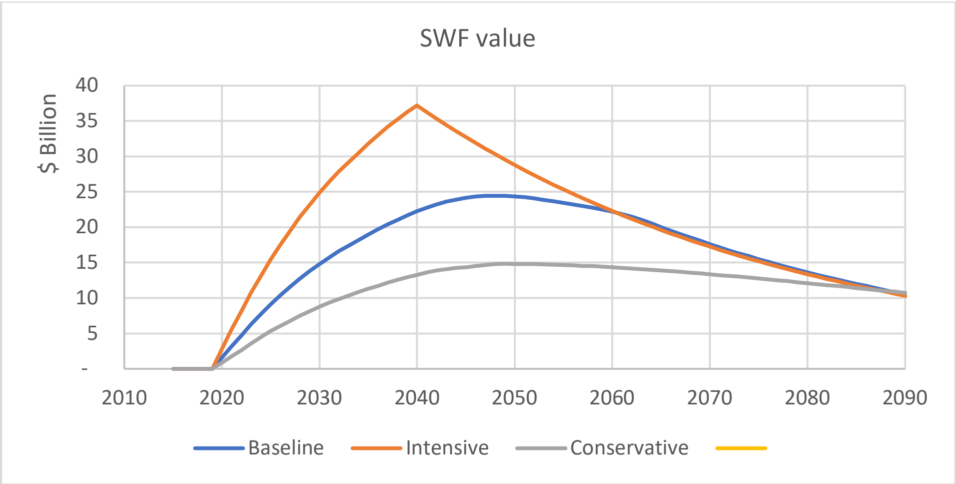

Figure 4. Growth in SWF value under the three scenarios in the benchmark scenario.

As can be seen in Figure 4, the value of the SWF is 31% higher in the intensive scenario than in the baseline scenario and 64% higher than in the conservative scenario. Note that in the first period the SWF value grows exponentially due to the increase in government transfers to the SWF, which were generated from the levy. When the NG is depleted, the only source for the SWF value is the rate of return on its investments. Thus, the growth rate is more moderate.

The government transfers are also higher in the intensive scenario. These transfers include income tax and royalties, which are transferred directly through the yearly budget and through a portion of the rate of return on SWF investments. We assume a 3% return on investments for the SWF. Note that this fund is infinite, and thus the transfers to individuals are infinite as well. In Table 4 we provide results for the four periods.

Table 4. Total government income transferred to individuals ($ billion).

Year	Baseline	Intensive	Conservative
2015–2040	23	36	14
2041–2065	25	23	16
2066–2090	12	11	11
2090–2115	6	6	7
Total	66	76	48

The calculation includes four 25-year periods, assuming 3% yield on the SWF investment. As seen in Table 4, the total transfers to individuals are higher under the intensive scenario. This is true except for the second and third periods, when the NG is totally depleted under the intensive scenario so the only source for government transfers is the rate of return on the SWF investment. In the fourth period when the NG is depleted across all three scenarios, the transfers are equal. In addition, the first generations receive higher transfers under the intensive scenario. In the second period when the NG is totally depleted under the intensive scenario, the transfers are higher under the baseline scenario.

The model results also showed that the intergenerational (3 generations) utility is higher under the intensive scenario ($1,221 million) than under the baseline scenario ($1,218 million) or under the conservative scenario ($1,205 million). Utility is higher in the first period in all three scenarios, and it decreases gradually due to NG depletion in the second period. The economic surplus is depicted in Table 6.

Table 6. Total economic surplus, 3 generations

	Baseline	Intensive	Conservative
Net benefit ($ billion)	1,194.7	1,367.8	948.5
SWF value ($ billion)	124	153	85
Total ($ billion)	1,318.7	1,520.8	1,033.5

In the long run, in the first period the economic surplus in the intensive scenario is higher than in the baseline or conservative scenarios. The results indicate that a higher extraction rate combined with an appropriate investment strategy is better than a conservative extraction rate. This result is consistent with the literature (see for example [9,19]).

5.2 Simulation results - Investing SWF in improving renewable energy productivity

Next, we extend the model by assuming that the government transfers a share of the tax income from NG directly to individuals, while the rest is invested in R&D aimed at increasing renewable energy productivity. Examples of this type of policy are public investment in energy storage facilities or in energy-efficient technologies[11].

The results are consistent with the results of the benchmark scenario, i.e., the total benefits are higher in the intensive scenario. The results also show a small improvement in utility levels under the three scenarios compared to the utility levels in the benchmark scenario[12]: 0.8% in the intensive scenario, 1% in the baseline scenario and 1.2% in the conservative scenario. Therefore, an increase in the productivity of renewable energy projects leads to an increase in electricity production, consumption and consumer utility, followed by an increase in economic welfare. Investing the SWF returns in R&D, which leads to improved productivity of renewable energy projects, may under some conditions be more beneficial than direct income transfer.

This result is consistent with Hartwick's weak sustainability rule stating that to offset declining stocks of exhaustible resources, public investment in reproducible capital is essential [9]. In addition, our results reconfirm the basic result of [8] that technological progress—including scientific and engineering processes and R&D—is a key factor in long-term sustainable economic growth.

6. Discussion and Conclusions

The results of the current study suggest some answers to the basic questions that were raised when the NG reserves were discovered in Israel, such as preferred extraction rate, export and pricing issues. These questions are relevant not only to Israel, but also to countries that seek to manage their windfalls objectively.

This research was motivated by growing concerns about the availability of exhaustible natural resource reserves in general, and NG in particular, not only for the current generation but also for

[11] Renewable energy usually depends on external factors, such as weather conditions, and is therefore considered less secure than fossil fuels.
[12] Note that we assumed that only the rate of return on the SWF investments is transferred to the individuals; thus the fund itself still exists.

future ones. Policymakers are required to define a comprehensive management strategy to find economic growth engines and overcome economic degradation. Starting from the intergenerational model developed by [20], we added the characteristics necessary for exhaustible natural resource management, based on [5, 22, 21]. We then applied the model to the Israeli NG sector. The advantages of the model developed above are: (1) it enables us to examine the intergenerational interactions and the effects of different variables on the economic welfare; (2) it allows comparing different extraction scenarios and evaluating the economic indicators emerging from different assumptions; and (3) it makes it possible to examine the interaction between different players in the energy economy (NG-extraction firms, electricity generation firms, the government and the consumers). This model can be used as a tool to define a sustainable policy that takes into account the welfare of current as well as future generations. The application to the Israeli case is given in Section 4.

The results of this study indicate that in Israel, a small open economy that was recently endowed with a windfall of NG, a higher NG-extraction rate combined with an appropriate investment strategy for NG profits is preferable from the economic perspective to a conservative rate. This result was determined with respect to consumer utility, producer profits, government transfers to the public, and NG-extraction firm profits. The results also indicate that under our assumptions, government income as well as the accumulated value of the SWF are higher in the intensive scenario. Transfers to individuals are also higher in the intensive scenario. This means that investing the income from an exhaustible resource can offset the decrease in welfare due to exhaustion of the resource. This is consistent with the literature, as in, for example, [9, 19].

Furthermore, we found that investment of returns from the SWF into R&D on renewable electricity production is also essential for sustainable economic growth and intergenerational equality. Investing returns from the SWF in renewable electricity production projects will lead to economic growth, as well as help build new energy sources for future generations. This result is timely and highly important, as the world’s transition to clean energy is only a matter of time. Countries are rapidly shifting to energy sources that emit less pollution. Substituting coal with NG could be a midterm solution for Israel until the country transitions to renewable energy.

The results of the current study are especially important today, as nations pursue the transition to less carbon-intensive energy sources. However, these results must be combined with a comprehensive strategic analysis of the impact of this policy on the different sectors. In addition, they must take into account such considerations as energy-efficiency aspects, strategic and geopolitical issues, energy security, and environmental effects.

The findings of this study have important policy implications. Policymakers should be aware of the demand for exhaustible resources, which are an essential source for energy production. Choosing an appropriate investment strategy for the SWF is important, as such a strategy can help avoid economic degradation resulting from depletion of the exhaustible resource.

Natural resources, including NG, belong to the public and should be utilized to raise the public's welfare and well-being. Moreover, decisions made by policymakers today will affect the welfare of the current and coming generations. Policy goals should be defined and prioritized, and management strategies should be set with respect to these goals.

In the last decade, the number of countries where natural resources, including NG, have been discovered has grown rapidly. The Israeli experience and the proposed model can be used in formulating a strategy for managing NG resources. The model proposed in the current paper can serve as a tool for other countries with newly discovered exhaustible resources that seek to identify resource management strategies and to choose the most appropriate policy to achieve their goals.

Finally, it is important to emphasize that this study was carried out independently and was not funded by any external body, making it objective and independent. Thus, the findings of this research can help policymakers assess and adjust their activities in the energy sector and consolidate a management strategy for the NG sector, which can also be applied to other sectors and other exhaustible resources.

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