Energy Strategy Reviews 45 (2023) 101032

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Accelerating emission reduction in Israel: Carbon pricing vs. policy standards

Ruslana Rachel Palatnik [a,b,c,*], Ayelet Davidovitch [d,c], Volker Krey [c], Nathan Sussman [e], Keywan Riahi [c], Matthew Gidden [c]

[a] Department of Economics and Management, The Max Stern Yezreel Valley College, Emek Yezreel 19300, Israel
[b] NRERC—Natural Resource and Environmental Research Center, University of Haifa, Israel
[c] IIASA—International Institute for Applied System Analysis, Laxenburg, Austria
[d] Porter School of Environmental Sciences, Tel Aviv University, Israel
[e] Department of International Economics, The Graduate Institute, Geneva and CEPR, Switzerland

ARTICLE INFO

Keywords:
Carbon emission reduction
2050 goals
Linked bottom-up-top-down modeling
Carbon pricing
Green policy standards
Renewable energy

ABSTRACT

The implementation of a carbon pricing policy to comply with GHG emission targets faces opposition in small economies. An integrated modeling exercise was carried out for Israel to assess the cost-effectiveness of GHG emission reduction options. Alternative policies in terms of carbon pricing and policy standards are evaluated. The results show that modest carbon pricing is effective. It achieves a 67% reduction in emissions, by 2050 relative to the reference year 2015, while having only a minor impact on economic growth. Policy standards currently proposed by the government will only reach a 40% emissions reduction in the same timeframe. Clean energy standards not coupled with carbon pricing may hinder efficiency but have a lesser impact on income distribution.

1. Introduction

With interest rates approaching zero and a significant slowdown in economic activity due to the COVID-19 pandemic, policymakers have begun considering green-infrastructure plans as a way to recover from the recession. As of January 1, 2021, over 75 countries enhanced their greenhouse gases (GHGs) mitigation targets declared under the Paris Agreement [1]. These commitments range from strategies, plans, and actions for low-emission development to economy-wide absolute emission reduction targets, demonstrating the growing ambition to address climate change [2,3].

What role should a small open economy play in carbon policy? This question is faced by Israeli policymakers. The country contributes about half a percent to global emissions of GHGs. In the energy sector, power generation is at a crossroads. Coal and oil are currently in the process of being replaced by natural gas (NG) and renewable energy (RE). The Industrial and transport sectors are also undergoing significant transitions. Abundant NG discoveries over the past decade have transformed this historically resource-poor country into a regional NG leader [4]. Israel now has sufficient NG supplies for the next thirty years. Before the NG discoveries, Israel's energy import bill was more than 5% of its gross domestic product (GDP). Currently, the development of a domestic supply of NG and its export has been contributing to the country's trade balance [5]. Ultimately, the process is expected to lead to cleaner energy and reduced environmental impacts.

Nevertheless, policymakers are confronted by many challenges that hinder their active commitment to carbon mitigation including the intermittent nature of RE, opposition to a carbon-tax-driven increase in energy prices, as well as uncertainty regarding the costs of energy transition and required infrastructure. Policymakers question the efficiency of carbon pricing in a heavily regulated energy sector. The common perception is that ongoing geopolitical tensions and the COVID-19 economic crisis leave little room for environmental considerations in general and carbon pricing in particular.

Meanwhile, the clean-energy industry has been gaining momentum. Globally, technologies that use energy more efficiently could deliver the same or better services with lower costs and risk [6]. Moreover, fossil fuels that now provide most of the energy generally cost more than the

* Corresponding author. Sustainable Economic and Environmental Development Research Center, The Max Stern Yezreel Valley College, Emek Yezreel 19300, Israel.

E-mail addresses: rachelpa@yvc.ac.il (R.R. Palatnik), ayelet.davidovitch@gmail.com (A. Davidovitch), krey@iiasa.ac.at (V. Krey), nathan.sussman@graduateinstitute.ch (N. Sussman), riahi@iiasa.ac.at (K. Riahi), matthew.gidden@gmail.com (M. Gidden).

https://doi.org/10.1016/j.esr.2022.101032
Received 15 June 2021; Received in revised form 19 July 2022; Accepted 31 October 2022
Available online 15 December 2022

modern renewable sources that have already taken over two-thirds of the world's power-plant market [7]. Recent years have been marked by turmoil in regional and global energy markets, with volatile oil prices, geopolitical tensions over oil and NG supply, and tightened environmental regulations. Early in 2020, when COVID-19 struck a blow to the global economy, the oil demand dropped by more than 20%, and prices collapsed. As countries embark on recovery, energy demand has begun to rise, and oil producers are curbing output to increase prices even further.

These developments offer policymakers opportunities to create a sustainable economy and make energy supplies resilient to catastrophic interruptions of supply [8]. In major economies such as China, India, the USA, and the EU, emerging evidence indicates that ambitious global climate protection based on least-cost energy resources can be profitable for the economy as a whole [9–11].

The research reported in this paper was initiated by the Israel Ministry of Environmental Protection. The study aimed to analyze the economic impact of alternative paths for GHG emission reduction in Israel. The project involved the Ministry of Energy and other relevant stakeholders, such that policy evaluation was based on a unique database and an up-to-date benchmark policy scenario. Ongoing dialogue with policymakers was accompanied by a rigorous analytical framework that helped shape the decision-making process. Specifically, the policy questions under consideration were: What would be the cost in terms of economic growth of transitioning to a green energy sector for the Israeli economy? Should a carbon tax be required, or would green standards be more effective in a small economy with regulated energy markets? Does a decade of accelerated investment in NG infrastructure in electricity and industry diminish the probability of a carbon-neutral energy sector?

The Israeli case study can support decision-making processes in small-open economies as well as in developing countries. Most of them share similar concerns about the impact of carbon pricing and clean energy reforms on energy security, electricity prices, income distribution, and economic growth [12]. As detailed below, our study used state-of-the-art modeling. The access to micro-level data on the energy sector, provided by the regulator, was crucial in calibrating the model. This study can be used, therefore, as a reference for cases when access to modeling or data is limited.

Gielen et al. [4] stated that well-designed transition policies should consider the characteristics of energy systems, encompassing both energy supply and demand. In this study, we use a modeling setup representing the Israeli energy system including the economic feedback effects of policies. The analysis is based on the countrywide application of the MESSAGEix integrated assessment modeling framework linked to the MACRO dynamic macroeconomic model [13]. For each of the policy scenarios, the framework estimates the required capacity investment, the optimal energy system configuration, and the resulting emissions, as well as demand response and the macroeconomic impact. It serves as a useful tool to inform the debate and facilitates the decision-making process for energy-related GHG emission reduction goals to be set by governments.

Implementing government pledges on GHG emissions depends on effective policies. The study supports the inference that by internalizing the externalities associated with GHG emissions, carbon pricing promotes cost-effective abatement, delivers efficiency incentives, and ameliorates rather than exacerbates government fiscal position [14]. Clean energy standards and emission reduction targets could be useful to support a carbon tax, but cannot substitute for it. The case study demonstrates that carbon pricing is more efficient than the policy standards that are under current consideration. However, this efficiency is achieved at a cost to energy consumers. To mitigate the regressive effect of carbon pricing, redistributing the added efficiency gains to low-income households is recommended.

The paper is structured as follows: Section 2 briefly reviews previous studies. Section 3 presents the methodology used in this study and outlines the research structure. Section 4 presents the key results. Section 5 discusses the findings and Section 6 concludes.

2. Previous studies

Energy is a crucial input for the economy. It is widely utilized as a production factor and consumed in various forms by households. For these reasons, any changes in the energy sector may significantly affect the economy. The challenge in modeling energy markets and policy is to provide an adequate means of capturing energy system effects, sectoral and macroeconomic impacts, and feedback effects [15]. The literature provides various approaches for combining economic and energy system models [15–17]. The following paragraphs provide a concise review of previous studies focused on energy-economic modeling.

Bottom-up engineering models include thorough descriptions of the technological aspects of the energy systems, including future improvements [18]. These descriptions include interactions among the numerous individual energy technologies that make up an economy's energy system, from the primary energy sources, via conversion and distribution processes, to the final energy use. A solution constitutes a partial equilibrium wherein energy demand is met in a cost-optimal fashion [19].

Top-down general equilibrium (GE) models, on the other hand, model the entire economy and emphasize the possibilities of substituting different production factors to maximize firms' profits [20]. The substitution possibilities between energy and other production factors are captured in production functions that describe changes in fuel mixes as a result of changes in relative prices, given substitution elasticities [21].

The top-down and bottom-up models represent two contrasting and widespread approaches to the quantitative assessment of energy policies. Linking them allows for the strengths of one model to complement those of the other [17].

Top-down analyses of the Israeli economy include the CGE model for Israel, the IGEM [22] that was developed and employed to analyze the economy-wide impact of climate change [23,24], and climate change mitigation policies in Israel [22,25]. Other CGE-based analyses include those of Luckmann [26] and Yerushalmi [27], which demonstrated the economy-wide costs of water scarcity for Israel. Siddig and Grethe [28] used a GTAP-based CGE model to analyze the costs of disruptions of the NG supply from Egypt to Israel.

The bottom-up energy-related models for Israel usually focus on a specific part of the energy system such as the electricity sector [29,30], NG, or oil [31], but do not address system-wide research questions. Therefore, due to expected shifts to NG and RE in power generation as well as to the electrification of transport and industry, a comprehensive representation of the energy sector and its links to the macro-economy is required.

We, therefore, complement the literature by providing a thorough macroeconomic assessment of climate mitigation policy in the Israeli energy sector. The MESSAGEix_IL-MACRO is the first modeling attempt to represent the Israeli energy sector as a whole, including a link to a macroeconomic model, MACRO, to retrieve feedback from the energy demand side. The present study broadens the scope of the policy alternatives and evaluates each of them with the rigorous tool of applied system analysis. This case study is representative of certain types of small open economies, characterized as energy islands, with substantial potential for generating intermittent renewable energy.

3. Materials and methods

3.1. MESSAGEix_IL model in a nutshell

MESSAGEix_IL is a country-level application of the integrated assessment modeling framework MESSAGEix developed over the past four decades [32]. Complete technical documentation of this open-source model is available online[1] and key input assumptions are summarized in the supplementary material. MESSAGEix is a dynamic, technology-based optimization model designed for medium-to long--term energy planning and policy analysis that provides a framework for representing energy systems with all their interdependencies and correlations (Fig. 1). MESSAGEix can describe the entire energy system, including resource extraction, trade, conversion, transmission, and distribution, as well as the provision of energy end-use services such as lighting, space conditioning, industrial process heating, and transportation on different scales, e.g., national [33] or global [13,34]. The optimization model is solved to find the least-cost solution for satisfying energy demand under various technical, economic, and environmental constraints.

To obtain macroeconomic feedback for changes in an energy system, MESSAGEix_IL is linked directly to the MACRO module of the MESSAGEix model introduced by Messner and Schrattenholzer [35]. MACRO maximizes the intertemporal utility function of a single representative producer-consumer through optimization [13]. The result is a sequence of optimal savings, investment, and consumption decisions. The main variables of the model are the capital stock, available labor, and energy inputs, which together determine the total output of an economy according to a nested production function with constant elasticity of substitution. Among other variables, the combined modeling framework MESSAGEix_IL-MACRO calculates the required capacity investment, the optimal energy system configuration, and the resulting emissions for each of the policy scenarios to obtain the carbon mitigation feedback regarding energy demands and overall economic performance.

3.2. Data

Based on interactions with the relevant stakeholders, we fed the MESSAGEix_IL-MACRO modeling framework the most recent data on the characteristics of the Israeli energy sector, as reported in Table 1 and the supplementary material. These include: the volume of NG reserves discovered offshore; energy taxes updated for 2019; power-generation capacity and lifetime by fuel; capital and operation and management (O&M) costs of NG and coal power plants, solar power stations, and storage, as evaluated by internal reports of the Ministry of Energy and the Public Utility Authority (PUA). The rich historical data also includes technologies in place, capacity, investment, and efficiency factors.

In the MACRO baseline calibration, Israel's population growth and GDP conform to official forecasts [36,47], while energy development is generated by the baseline scenario in MESSAGEix_IL. The discount rate was based on estimations of the Israeli National Economic Council for public investment in various sectors. The estimated discount rate in the sector "National infrastructures with natural monopoly characteristics in the field of communications, energy, water and agriculture; Green and renewable energy" sector is currently negative (−0.41%) and gradually increases to two percentage points by 2050 (see Supplementary Material).

3.3. Research design

The research and analysis described here included ongoing and iterative participation of relevant stakeholders (Fig. 2) and in particular close cooperation with the Ministry of Environmental Protection and the Ministry of Energy.

The future development of the Israeli energy sector through 2050 was modeled in collaboration with stakeholders and in line with official policy plans, e. g., for the share of electric transport, the share of renewable energy, and coal in power generation. Using this input, MESSAGEix_IL generated the "baseline" scenario for the future development of the energy sector in Israel through 2050. The "baseline" scenario generated by MESSAGEix_IL served for calibration of the aggregate macroeconomic model- MACRO.

Next, alternative future policies were imposed in MESSAGEix_IL as external shocks to the energy system. Among these were a higher share of power generation from RE, complete electrification of the transport sector by 2050, and carbon pricing. In response to those shocks, the cost minimization model of MESSAGEix_IL re-optimized the energy mix. The resulting energy prices were used as input to MACRO, which generated final demands and transferred the energy demands back to MESSAGEix_IL. The models were run until the energy quantities converged. The results represent alternative trajectories of energy sector development in Israel that consider the direct economic costs of energy-related GHG emissions reduction. The year 2015 is the most recent "historical" period in the model, which runs in five-year steps. Therefore, the first output of the MESSAGEix_IL-MACRO framework is obtained for the year2020.[2] The results of the scenarios were presented to the stakeholders that commented, and in some cases altered the assumptions for alternative scenarios. The scenarios were reevaluated accordingly.

3.4. Scenarios

The Ministry of Energy and the government are currently discussing several energy policy scenarios that have not yet been finalized. The plan for Energy Economy Objectives for 2030 [45] provides a cost-benefit analysis of transformations in three sectors: (1) eliminating coal from the energy mix for power generation while increasing the share of NG to 70% and of RE to 17%, (2) increasing the NG share for the production of energy and steam in the industrial sector, and (3) shifting to electric vehicles and NG-powered trucks. A positive net economic benefit was estimated in this plan [45]. We expand the scope and tools of the analysis by employing a multi-scenario analysis to identify the economic prospects of clean energy trajectories for Israel and the associated changes in GHG emissions under climate mitigation policies. We also extend the analysis beyond 2030 to 2050. The key assumptions for each scenario are summarized in Table 2.

Starting from the baseline scenario, three alternative policy scenarios were analyzed. The policy standards scenario implies reaching the following clean energy goals by 2050: 85% of RE in the energy mix for power generation, complete electrification of transportation, and a complete phase-out of coal by 2030. The carbon tax scenario introduces an increase in carbon pricing in line with the mid-range of EPA [44]. We used a relatively modest trajectory for the carbon tax scenario compared with recent evaluations of the social cost of carbon (estimated at USD 100–200 [48],) and relative to the carbon price estimated at USD 75, required for achieving global net-zero carbon emissions, [49]. Carbon taxes were added to existing energy taxes. No green policy standards are imposed in the carbon tax scenario. The third scenario "Policy + Tax" combines the policy standards and the carbon pricing scenarios.

Although MESSAGEix_IL reflects energy-related carbon emissions in detail, other sources of GHGs, such as agriculture, waste, and land-use change are included in the current version of the model. Therefore, the analysis below reflects the potential change in about 85% of Israel's GHG emissions.

4. Results

Fig. 3 shows the GDP growth rate relative to the 2015 baseline and the estimated GHG emissions for each of the three scenarios, starting from the observed year 2015 and with five-year intervals until 2050. According to the official, pre-Covid-19 assumptions [47], from 2015 to 2050 the GDP is projected to grow by about 140% in the Baseline Scenario (Fig. 3a), while the population will almost double. The

[1] https://docs.messageix.org.

[2] This is due to lags in obtaining historical data.

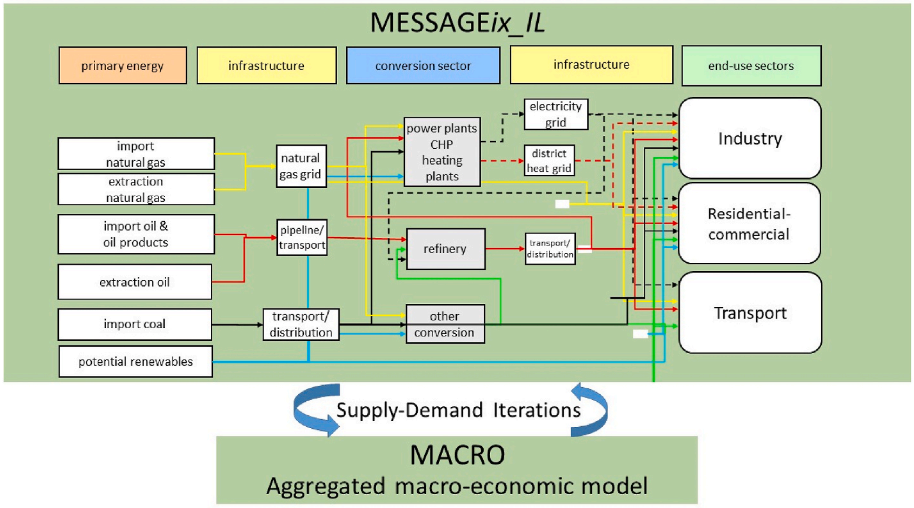


Fig. 1. Overview of MESSAGEix_IL - MACRO system.

Table 1
Main data sources for adjustments in MESSAGEix_IL-MACRO.

Data	Source
Population growth	Medium and high scenarios [36]
GDP growth	Medium [37]; High [38]
Energy prices until 2030	World Bank [39]
Energy prices 2031–2050	[40]
Interest rate	Israeli National Economic Council (unpublished)
Energy taxes Israel	Ministry of Energy, Fuel Department (4/2019)
Coal power generation in Israel	Ministry of Energy Chief Scientist
Storage costs Israel	Ministry of Energy Chief Scientist
NG Capital cost and OM cost	Ministry of Energy Chief Scientist
Coal Capital cost and OM cost	Ministry of Energy Chief Scientist
Solar Capital cost and OM cost	Ministry of Energy Chief Scientist
Technology efficiency	Ministry of Energy Chief Scientist
Power plants lifetime	Ministry of Energy Chief Scientist
NG reserves	[41]
NG export till 2050	[41]
Historical data on energy balance, Israel	EIA [42], and CBS
Elasticities of electricity demand	BOI [43]
Emissions factors	Ministry of Environmental Protection
Carbon Tax	[44]
Electricity Transportation	Ministry of Energy (personal communication)
Renewable energy goals	[45,46]

corresponding growth of energy-related GHG emissions,[3] as estimated by MESSAGEix_IL, is 35% (Fig. 3b). Evidently, in the baseline scenario GDP growth is significantly higher than the increase in GHG emissions. Therefore, partial decoupling between economic growth and carbon emissions in the Israeli economy may be achieved if currently planned policies are implemented. Nevertheless, the moderate growth in emissions in the baseline scenario greatly exceeds the international aim of reaching net-zero GHG emissions by 2050.

The estimated policies not only prevent increases in GHGs but also significantly reduce emissions (Fig. 3b): Policy standards reduce energy-related GHG emissions by 40% relative to 2015, carbon pricing reduces emissions by 67%, and the combined policy standards and carbon pricing scenario adds 5% to the reduction achieved by carbon pricing alone.

MESSAGEix_IL allows investigating the channels by which the scenarios affect the energy sector. We present the change in key energy indicators and their determinants by scenario.

Fig. 4 depicts power generation and the share of solar energy in the energy mix. The baseline assumes reaching 17% solar energy by 2030 and maintaining this share after that. The policy standards and policy + tax scenarios impose the green policy standard of reaching 85% of solar energy in the power generation mix. No such target is imposed in the carbon tax scenario, in which solar power endogenously reaches 65%.

In all alternative scenarios, power generation appears to rise significantly compared to baseline (Figs. 4 and 5). The main force driving this change is the complete electrification of the transport sector that is achieved not only when explicit green policy standards are imposed, but also in the carbon pricing scenario. Storage needs in solar-intensive scenarios also contribute to growing power generation to compensate for the intermittency of this RE source. Additional differences between the scenarios are attributed to variations in the electrification of the industrial sector.[4]

Focusing on the energy mix in power generation, the main differences between the scenarios lie in the composition of NG vs. solar. In all the alternative scenarios, the share of solar in power generation increases significantly at the expense of NG, while coal is completely crowded out. The transition to solar includes a corresponding increase in storage that is required for a reliable supply of electricity. The results suggest that NG can bridge the transition to cleaner power generation. Moreover, carbon pricing that levies taxes on fossil fuels according to their carbon content, allows a more gradual transition to solar than in the policy standards scenario. In this scenario, even in 2050 NG comprises 35% of the energy mix in electricity production, compared to only 15% in the green policy standards scenario (Fig. 5). Thus, carbon pricing stimulates higher utilization of Israel's vast NG reserves, providing energy security and taking advantage of existing natural resources and the related infrastructure.

The transportation sector is relatively flexible in terms of energy sources. It can switch relatively quickly to cleaner energy and energy-

[3] The analysis so far covers about 85% of GHGs in Israel that result from energy-related processes. The rest is caused mainly by agriculture, land use change and waste. Furthermore, the model does not take into account the effect of structural changes in the economic sectors on the composition of employment.

[4] Israel is somewhat unique in terms of its population growth therefore its GDP and absolute energy consumption increase faster than other OECD economies, but may well represent less developed economies considering GHG reduction policies.

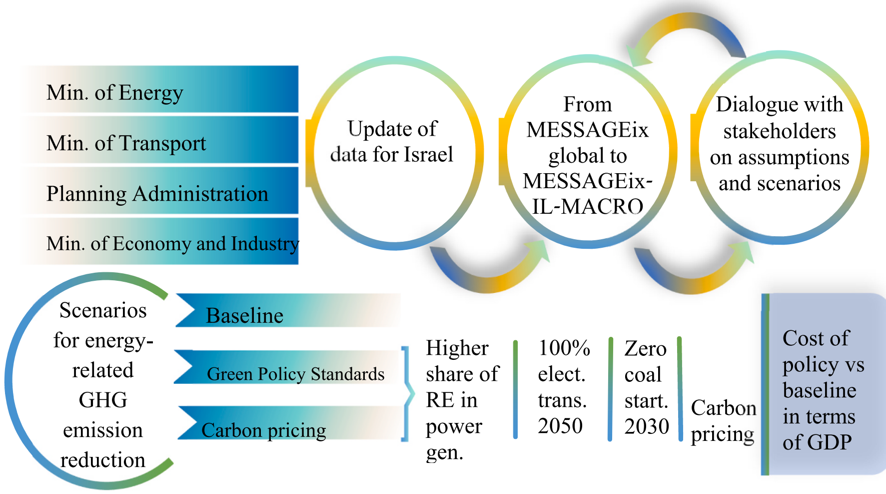


Fig. 2. Schematic diagram of the research design process and stakeholder interaction.

Table 2
Scenario assumptions.

Policy dimension		Baseline	Policy Standards	Carbon Pricing	
Socio-economic	*Population* (average annual growth)	1.7% [36]	Follows baseline		
	GDP (average annual growth)	2.5% [37]			
Power generation	*RE*	17% from 2030 on	85% in 2050	No green policy standards	
	Coal	Reduction of the capacity of coal power plants by 2030, remaining 3400 MW available till 2050	Graduate reduction to 0 by 2030		
	NG	export of 25% of reserves by 2050	No limit on NG capacity after 2025		
Electric Transport		30% in 2050	100% in 2050		
Carbon tax ***(Average annual in 5 years, per ton*** CO_{2eq}***)***		No Carbon Pricing	No Carbon Pricing	2020	$0
				2025	$23.3
				2030	$48
				2035	$53
				2040	$58
				2045	$62
				2050	$67
				2055+	$69

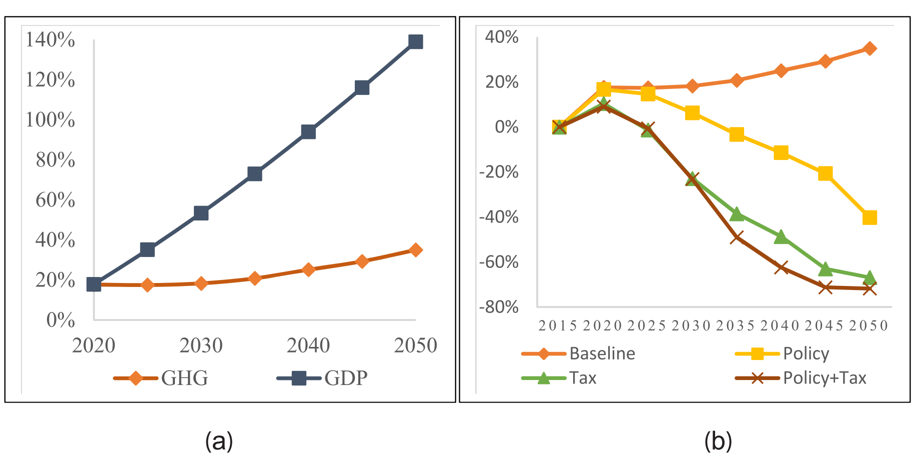


Fig. 3. a. Decoupling of economic and emission growth rates in the Baseline scenario. b. Projected GHGs by scenario vs 2015 level.

efficient technologies. In addition, the thermal efficiency of internal combustion engines is about 20%, whereas electric vehicles can achieve 85 to 98% efficiency. A combination of these two processes makes it possible to meet the projected increase in transportation demand while significantly reducing fuel consumption and corresponding emissions. This sector undergoes full electrification not only in the green policy standards scenario but also in the carbon pricing scenario (Fig. 6). Electrification in conjunction with decarbonization of the power sector

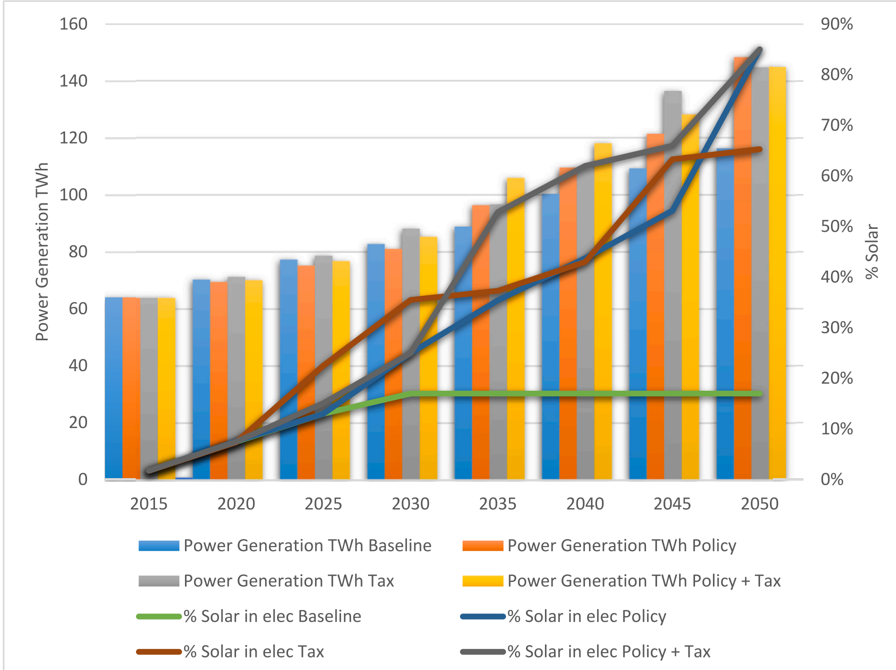


Fig. 4. Electricity generation and share of solar by scenario.

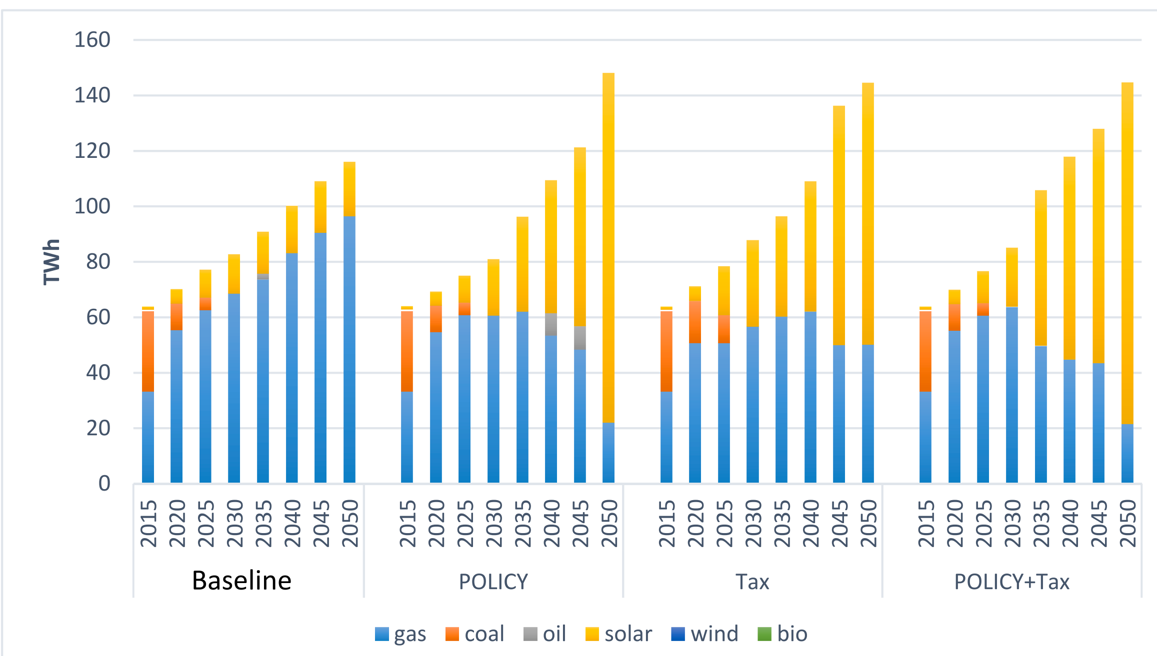


Fig. 5. Electricity generation by energy source in Terawatt-hours (TWh).

offers a cost-efficient mitigation strategy because fossil fuels get penalized more significantly. Nevertheless, the path to complete electrification of transportation varies among the alternative scenarios. In the green policy standards scenario, where no carbon pricing is imposed, NG serves as the main fuel during the transition period. Under the carbon tax scenario, however, NG is used for a shorter period, allowing cleaner biofuels as another transitional bridge.

Israeli policymakers have not defined green policy standards for the industrial sector. Accordingly, no targets were imposed in either the baseline or the policy standards scenario. Therefore, total energy use in industry is not altered by the policy standards scenario compared to the baseline (Fig. 7). Nevertheless, more NG is used in industry in the alternative scenarios than in the baseline. Industry ends up using NG that was freed from power generation.

Not only does carbon pricing stimulate the industry to increase its utilization of NG instead of petroleum products, but it also raises energy efficiency. Here, the advantage of carbon pricing over green policy standards is most evident. The ubiquitous nature of energy production and the use and variety of carbon sources in today's economy means that conventional technologies and standards for performance will not be possible [14]. Carbon pricing has an economic advantage because of the flexibility it offers and the incentive it provides to all sources of GHGs.

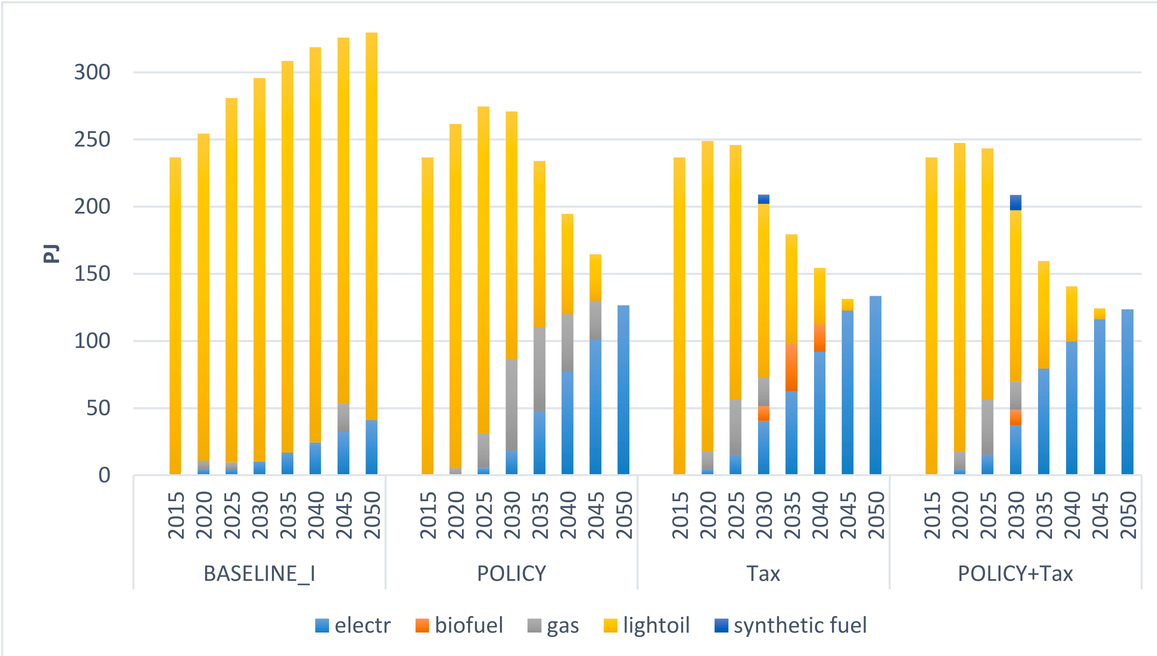


Fig. 6. Final energy by energy carrier in transport (PJ).

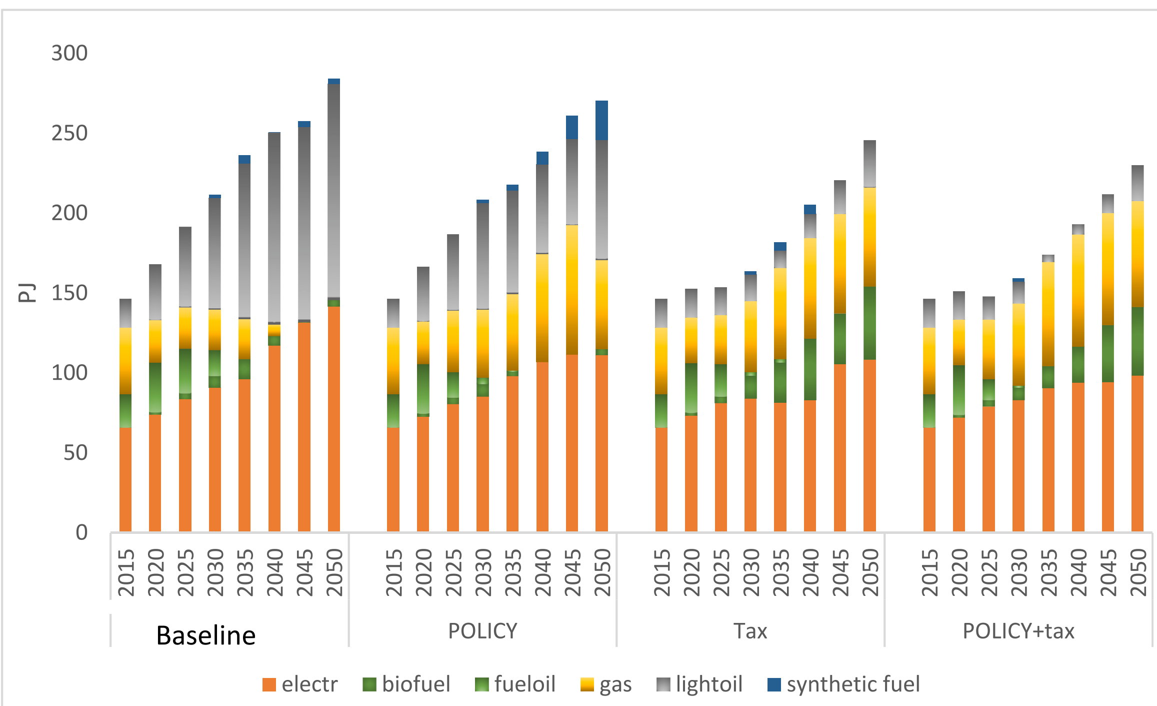


Fig. 7. Final energy by energy carrier in the industry (PJ).

Fig. 8 compares the total final energy consumption (TFC) between 2020 and 2050 in the baseline and alternative scenarios. TFC is significantly lower under the carbon standards and pricing scenarios relative to the baseline. This is due mainly to the reduction in petroleum products, which are only partially replaced by electricity. As mentioned above, electric transport is much more energy-efficient than transport using internal combustion engines. In addition, carbon pricing supports the penetration of RE and NG not only in electricity but also in the industrial sector.

In the above paragraphs, we investigated the impact of green policy standards and carbon pricing on energy-related carbon emissions, and the underlying sectoral transformations that lead to emission reduction. Now we consider the following central questions: What are the economic costs of achieving this mitigation? More importantly, do these costs vary by the type of policy in place? Fig. 9a shows the GDP by scenario, while Fig. 9b zooms in on the percent change in GDP by scenario vs. baseline.

Note that the significant reduction in GHG emissions comes at a

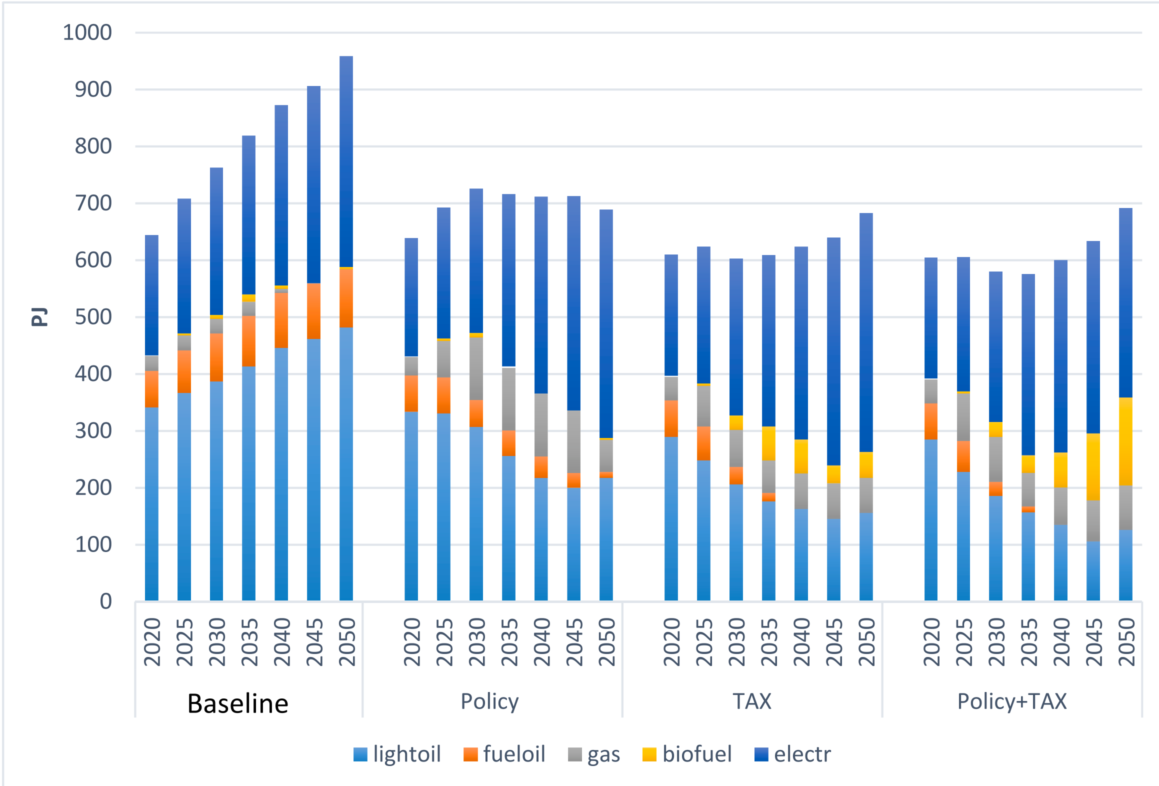
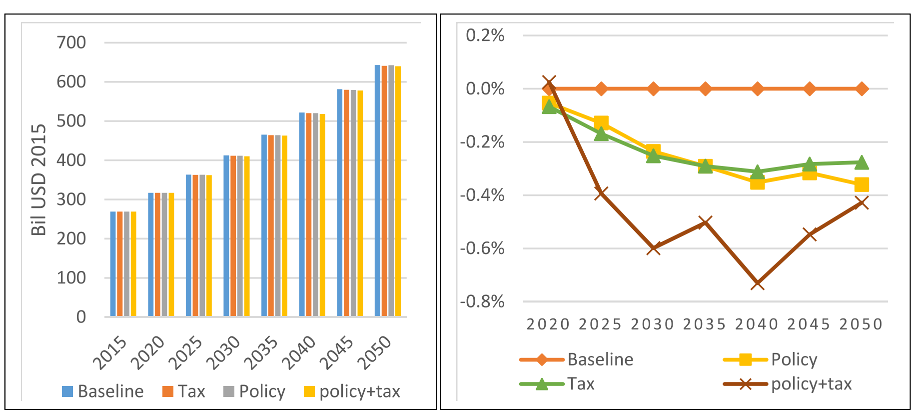


Fig. 8. Total final energy consumption (TFC) by energy carrier in PJ.



(a) (b)

Fig. 9. a. GDP by scenario in Billion USD 2015. b. GDP percent change vs baseline by scenario.

negligible direct cost in terms of GDP. Carbon pricing appears to be the most efficient policy, achieving about 20% higher mitigation (Fig. 3b) at a lower cost in terms of GDP compared to green policy standards (Fig. 9b). The combination of green policy standards and carbon pricing performs slightly better in terms of emission reduction, though at lower GDP growth across the planning horizon.

As can be seen in Fig. 10, energy intensity is the main energy indicator for tracking the plausible transformation of energy and the economy. Energy intensity is calculated as the million tons of oil equivalent (MTOE) of TFC per unit of GDP estimated in USD 2015 PPP.[5] As energy intensity declines, less energy is required for economic activity. A gradual reduction of 27% in energy intensity is achieved in the baseline scenario. In contrast, green policy standards or carbon pricing lead to a reduction of about 45% in 2050 relative to baseline. Thus, the alternative policy scenarios exhibit a significant decline in TFC (Fig. 8), whereas the GDP changes mildly, if at all (Fig. 9).

The projected change in energy prices can shed additional light on the impact of the transition (Fig. 11a and b).

Fig. 11a shows the oil, coal, and NG price index in the tax scenario relative to the baseline scenario. The changes in the prices of these fossil fuels are mainly due to imposing carbon pricing according to the carbon content of each of the fuels. As Israel has no domestic coal and oil production, the prices of these fuels are essentially the exogenously assumed (global) market prices [50] plus the carbon tax. In contrast, NG prices result from an equilibrium in which demand responds to a change

[5] Purchasing power parity.

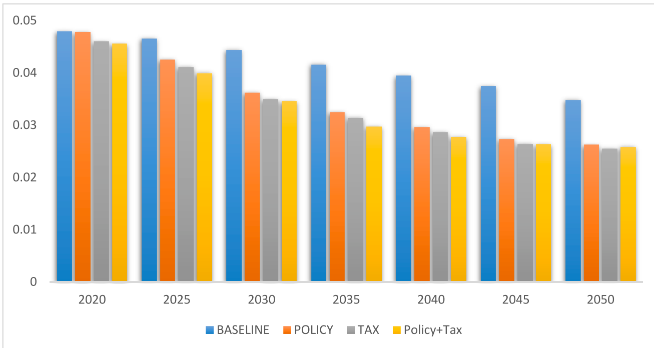


Fig. 10. Final energy intensity [TFC in MTOE per GDP in USD 2015 PPP] by scenario.

in the relative price of this energy source. The moderation in the rise in NG prices after 2030 can be explained by the fact that the tax stimulates the transition to less polluting fuels in both electricity generation and industry.

Fig. 11b depicts the price of electricity as an index of change in the alternative scenarios vs. baseline. In an optimization model such as MESSAGEix, commodity prices reflect the extent to which the objective function – in the case of MESSAGE, the total discounted system costs – would change if the demand constraints were relaxed by one unit (i.e. at the margin). These changes also depend on other constraints such as green policy standards and carbon pricing. The sharp changes in prices are typically due to investments triggered in specific periods in response to policies and/or taxes. In the green policy standards scenario, such a change in investments is triggered in 2030, after which prices return to baseline. Under carbon pricing, the cost of producing electricity from NG increases continuously, as reflected in the electricity price. As of 2045, this no longer seems to be the case.

Accordingly, the price of electricity can reflect the distribution effect of standards vs. carbon pricing. Policy standards boost investments too early, leading to a loss of profits for entrepreneurs, and ultimately to lower economic efficiency because of abandoned capital. Yet, households might experience an overall lower price increase under the standards scenario than under the carbon pricing scenario. Therefore, in the case of carbon pricing, a compensation scheme for low-income population groups could be considered. The efficiency gains and the revenue from a carbon tax or a cap-and-trade program with an allowance auction should at least be partially utilized to compensate low-income households that suffer disproportionally from an increase in electricity prices.

The government take from the carbon tax (Fig. 12) has an inverse U shape, as the tax per ton of CO_2 equivalent increases, while GHG emissions are projected to decline over time. In the post-COVID-19 economy, the government might seek new sources to cover the rising debt to GDP ratios and might consider raising taxes. Unlike most other distorting taxes in the economy, carbon tax prices the GHG externality, so that decisions on the variety of carbon-related economic activities take this external cost into account. Therefore, a carbon tax can serve as an efficient means to reduce the debt burden.

5. Discussion

Policymakers around the world are in the process of establishing national development plans for 2050 to combat climate change. Carbon pricing, which imposes a levy on each ton of carbon, is planned to cover a fifth of the world's emissions [51]. The current article reports the outcome of an investigation carried out in cooperation with stakeholders to analyze the implications of climate policy in a small, open economy. Like policymakers everywhere, Israeli policymakers face a dilemma regarding carbon pledges and the choice of emission mitigation options: whether to set green policy standards or use carbon pricing. Policymakers must consider the cost-effectiveness, political acceptability, and distributional effects of these options.

To support the decision-making process, we simulated the adoption of energy-related carbon emission reduction standards and pricing policies. We then analyzed their impact on economic growth in Israel using MESSAGEix_IL-MACRO, an original dynamic integrated energy-macroeconomic modeling framework. This case study is particularly representative of certain types of small, open economies, characterized as energy islands with substantial potential for generating intermittent renewable energy.

The results of four cases were analyzed. The baseline scenario

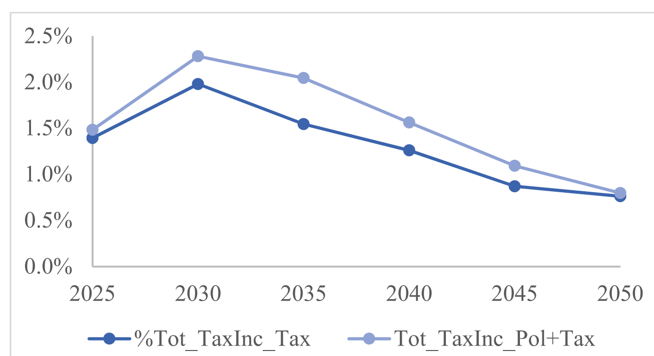


Fig. 12. Income of carbon tax from energy-related GHG emissions.

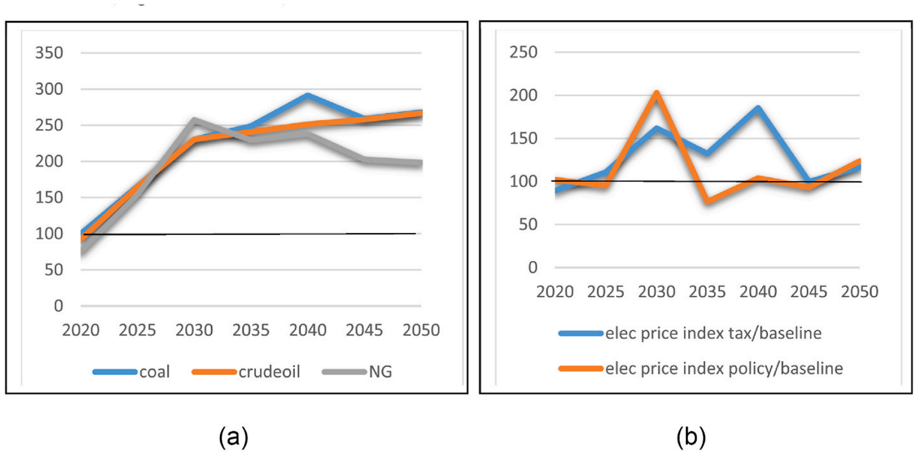


Fig. 11. a. Price index tax vs baseline scenario of primary energy. b. Electricity price index tax and standards vs baseline scenario.

developed in collaboration with stakeholders served as the starting points for three policy scenarios: green policy standards, carbon pricing, and a combined scenario of green policy standards and carbon pricing.

Our results show that carbon pricing raises the share of renewable electricity, mainly solar power, from 5% of supply today to 65% by 2050. Coal use will end, and oil will decline rapidly, while cleaner NG will remain central, representing another important step in the decarbonization of electrification. The results show that in the carbon pricing scenario, the rate of electricity use in total final energy consumption increases from about 30% at present to about 60% in 2050. This result is in line with recent studies [52,53]. The latest BP analysis also showed that global decarbonization increases the share of energy from electricity from about a fifth in 2018 to just over half in 2050 [54].

This energy architecture will ultimately bring immense benefits. Carbon emission standards or carbon pricing can reduce energy-related GHG emissions by about 40 and 67% respectively, by 2050 relative to 2015, with only a minor direct cost in terms of GDP growth. A significant decline in emissions can be efficiently achieved by rather modest carbon pricing. This result contributes to the recent evidence of carbon pricing efficacy [55].

The study provides support for adopting carbon pricing as a key mitigation policy that acts consistently across all sectors of the economy. By pricing CO_2 emissions (or, equivalently, by pricing the carbon content of the three fossil fuels—coal, petroleum, and natural gas), governments will incentivize firms and consumers to find and exploit the least-cost ways of reducing emissions. Carbon pricing provides incentives for investing and developing new technologies, processes, and innovations to mitigate emissions efficiently. Uniform technology and performance standards can—in principle—be effective in achieving some environmental purposes. Technology standards and other more specific policies can help overcome barriers in some sectors and can be useful as a complement to carbon pricing [56]. Yet, given the ubiquitous nature of GHGs from diverse sources in an economy, it is unlikely that technology or ordinary performance standards can serve as the centerpiece of a meaningful climate policy [57].

The results show that clean energy standards that are not coupled with carbon pricing may have a smaller impact on income distribution, but will entail efficiency losses. Therefore, the efficiency gains of carbon pricing should at least partially fund support for low-income population groups [58]. Our main recommendation for policymakers is to use carbon taxation as the main instrument in climate policy. In any case, it is crucial that if both carbon targets and pricing are set, they do not contradict but rather complement each other.

Policymakers are also concerned with energy security. Increased use of domestic RE reduces reliance on imported coal and oil. The main source of RE in Israel is solar energy. The potential of wind energy has not yet been proven, and hydroelectric power is infeasible in an arid region like Israel. Nuclear power plants are also infeasible in the current geopolitical reality. Accordingly, to meet the goals of clean power generation, demand management and electricity storage is of major importance. The results indicate that carbon tax policy also offers co-benefits for energy security [59]. Optimization based on a carbon tax preserves a higher rate of NG for domestic users than policy standards. Therefore, by exploiting emission mitigation options across the entire economy, a carbon tax policy would exploit Israel's NG resource endowments efficiently and offer a higher return for NG-related capital. This result can apply to additional economies that produce NG and are reluctant to set carbon pricing.

6. Conclusions

The analysis reveals several important conclusions. The carbon pricing to reduce GHG emissions by 2050 represents an exceptional opportunity for long-term strategic planning in Israel and elsewhere. Significant reductions in GHG emissions can be achieved by electrification of the economy while basing power generation on renewable energy sources. Achieving these goals involves investment, which, if implemented optimally, will reach both emission reduction goals and economic growth. There is synergy between the adoption of a carbon tax, green policies, and investments in infrastructure. Carbon tax revenues can partially fund investment infrastructure to boost employment and growth, especially post-COVID [60–62].

The transport sector is responsible for more than two-thirds of Israel's fossil fuel final energy consumption. In addition, Israel suffers from decades-long underinvestment in its transportation infrastructure. Given the urgency of solving road congestion and the ongoing increase in the number of new vehicles on the roads every year, as driven by demographic and economic growth, we recommend the government to address the rapid electrification of light-duty vehicles and public transport as its most important budgetary commitment, requiring immediate implementation. Accordingly, we call for investment in electric and efficient public transportation. This investment is crucial to serving as a substitute for travel by car which will be affected by carbon pricing. In addition, the COVID-19 crisis has shown that many daily trips, may not be necessary. Providing support for some degree of working from home in the public and private sectors can be considered an additional aspect of the green standards toolkit. Work-from-home standards may be cost-effective in reducing both congestion and pollution, as well as the regressive impact of carbon pricing.

Infrastructure that allows transmission for electricity storage and supply can also contribute to solving the challenge of a high share of solar energy in power generation.

The industry is also responsible for a significant share of emissions. To make the most of Israel's offshore NG reserves, the government is subsidizing the investment in NG infrastructure for energy-intensive industries. The utilization of NG is indeed preferable in terms of pollution when compared to other fossil fuels. Carbon taxation will enable Israel to exploit NG more than the policy target scenario. Nevertheless, current planning of future investment in NG infrastructure should be commensurate with the carbon pricing scenario and not exceed it. In addition, given the projected reduction in the use of oil products evident in all the scenarios, the government should reconsider the industrial development plans for oil refineries.

Hence, the Israeli government should play a bigger role in how businesses respond to climate change in the future. Carbon pricing and climate-friendly rules will determine how quickly companies decarbonize and how costly it will be for those that fail to do so. Decarbonization offers plenty of opportunities for Israeli entrepreneurs, among them, developing new technology, becoming more carbon-efficient than competitors, and selling green products to consumers. Even without support from regulation at home, many Israeli innovators in fields such as rooftop solar panels, novel biofuels, and storage technologies have already seized opportunities abroad. Carbon pricing and supporting standards will bring these benefits to society at home.

In addition, a reduction in GHG emissions reduces local pollutants [63], bringing about improved air quality and gains in health and labor productivity. Moreover, economic and social benefits from mitigating climate change and avoiding climate impacts are sure to follow [64].

Despite the positive macroeconomic outlook generated by our model, the threat of a poorly managed transition still looms. Several risks stand out. Special interest groups, among them the local NG monopoly, powerful refineries, and ongoing resistance to active decarbonization policy stand to lose from adopting GHG policy goals. Confronting these challenges requires strong political will. Adverse distributional outcomes that affect low-income households may induce political resistance. The overall benefits of decarbonization to the economy will enable governments to redistribute these gains to offset the distributional consequences of carbon pricing.

The political responses to carbon pricing in most countries have been and will continue to be largely a function of issues and structural factors that are beyond the scope of environmental and climate policies [55,57,65]. Some governments, particularly in Europe, have been attaching green strings to COVID-19 corporate bail-out packages and have promised to invest more in the low-carbon economy. As the Israeli economy starts to bounce back, policymakers should consider how measures can be designed to best support the transition to a low-carbon economy. It is also possible that the ongoing COVID-19 crisis that has dramatically escalated the budgetary deficit in Israel and elsewhere may increase the political feasibility of carbon tax as a new source of revenue that also corrects for a harmful externality.

Credit author statement

Ruslana Rachel Palatnik: Conceptualization, Formal analysis, Investigation, Writing - Original Draft; Ayelet Davidovitch: Software, Formal analysis, Investigation; Volker Krey: Conceptualization, Methodology, Writing - Review & Editing; Nathan Sussman: Conceptualization, Writing - Review & Editing; Keywan Riahi: Conceptualization, Methodology, Supervision; Matthew Gidden: Methodology, Software, Formal analysis.

Funding

This work was supported by the Ministry of Environmental Protection and the Israel Democracy Institute, Israel s a part of the project “Sustainable economic development”.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank Dr. Gil Proactor, Mr. Yuval Laster, Mrs. Daphna Aviram-Nitzan, Mr. Ron Kammara, Ms. Sophia Igdalov, Mr. Elior Bliah, and Mrs. Hila Shoef and the Energy Research Program at IIASA for fruitful cooperation and valuable input. The authors thank Mr. Jason Wang and Ms. Charlotte Davis for their assistance in proofing the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2022.101032.

References

[1] UNFCCC, Communication of long-term strategies [Online]. Available: https://unfccc.int/process/the-paris-agreement/long-term-strategies, 22 1 2020.
[2] UNFCCC, Nationally Determined Contributions under the Paris Agreement, United Nations, 2021.
[3] European Commission, The European Green Deal, European Commission, Brussels, 2019.
[4] H. Abu-Kalla, R.R. Palatnik, O. Ayalon, M. Shechter, Hoard or exploit? Intergenerational allocation of exhaustible natural resources, Energies 13 (24) (2020).
[5] R.R. Palatnik, T. Tavor, L. Voldman, The symptoms of illness: does Israel suffer from “Dutch disease”, Energies 12 (14) (2019).
[6] D. Gielen, F. Boshell, D. Saygin, M.D. Bazilian, N. Wagner, R. Gorini, The role of renewable energy in the global energy transformation, Energy Strategy Rev. 24 (2019) 38–50.
[7] IEA and IRENA, Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System, 2017.
[8] SDSN, FEEM, Roadmap to 2050 A Manual for Nations to Decarbonize by Mid-Century, September, 2019 [Online]. Available: https://roadmap2050.report/?mc_cid=85727aa78d&mc_eid=b1ed9d2da0.
[9] N. Ndrc, The 13th Five-Year Plan for Energy Development, NDRC and NEA, Beijing, 2016.
[10] C. Kemfert, Germany must go back to its low-carbon future, Nature News 549 (7670) (2017) 26.
[11] CCC, Net Zero: the UK’s Contribution to Stopping Global Warming, Committee on Climate Change, London, 2019.
[12] D. Finon, Carbon policy in developing countries: giving priority to non-price instruments, Energy Pol. 132 (2019) 38–43.
[13] O. Fricko, P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century, Global Environ. Change 42 (2017) 251–267.
[14] R.N. Stavins, Carbon taxes vs. Cap and trade: theory and practice, in: Harvard Project on Climate Agreements, Mass., Cambridge, 2019.
[15] P.I. Helgesen, A. Tomasgard, From linking to integration of energy system models and computational general equilibrium models e Effects on equilibria and convergence, Energy 159 (2018) 1218–1233.
[16] C. Arndt, R. Davies, S. Gabriel, K. Makrelov, B. Merven, F. Hartley, e. al., A sequential approach to integrated energy modeling in South Africa, Appl. Energy 161 (2016) 591–599.
[17] C. Bohringer, T.F. Rutherford, Combining bottom-up and top-down, Energy Econ. 30 (2) (2008) 574–596.
[18] J.C. Hourcade, M. Jaccard, C. Bataille, F. Ghersi, Hybrid modeling: new answers to old challenges - introduction to the special issue of the Energy Journal, Energy (2006) 1–11.
[19] B. Müller, F. Gardumi, L. Hülk, Comprehensive representation of models for energy system analyses: insights from the energy modelling platform for Europe (EMP-E), Energy Strategy Rev. 21 (2017) 82–87, 2018.
[20] R.R. Palatnik, The economic value of seawater desalination—the case of israe, in: l Economy-wide Modeling of Water at Regional and Global Scales: Advances in Applied General Equilibrium Modeling, Springer, Singapore, 2019.
[21] M. Kirchnera, M. Sommer, K. Kratena, D. Kletzan-Slamanig, CO2 taxes, equity and the double dividend – macroeconomic model simulations for Austria, Energy Pol. 126 (2019) 295–314.
[22] R.R. Palatnik, M. Shechter, Assessing the impact of greenhouse gas emission controls within the framework of a general equilibrium model of the Israeli economy, Economic Quarterly 55 (4) (2008) 545–573.
[23] Z. Baum, R.R. Palatnik, I. Kan, M.W.0 Rappaport-Rom, Economic impacts of water scarcity under diverse water salinities, Water Economics and Policy (WEP) 2 (1) (2016).
[24] A. Davidovich, R.R. Palatnik, O. Ayalon, M. Shechter, An assessment of the impact of climate change on the insurance market: global and local analyses, in: Annual Conference of the European Association of Environmental and Resource Economists EAERE 21, Finland, Helsinki, 2015.
[25] R.R. Palatnik, M. Shechter, The Israeli economy and potential post-kyoto targets, Isr. Econ. Rev. 8 (1) (2010) 21–43.
[26] J. Luckmann, H. Grethe, S. McDonald, A. Orlov, K. Siddig, An integrated economic model of multiple types and uses of water, Water Resour. Res. 50 (5) (2014) 3875–3892.
[27] E. Yerushalmi, Using water allocation in Israel as a proxy for imputing the value of agricultural amenities, Ecol. Econ. 149 (2018) 12–20.
[28] K. Siddig, H. Grethe, No more gas from Egypt? Modeling offshore discoveries and import uncertainty of natural gas in Israel, Appl. Energy 136 (2014) 312–324.
[29] A. Solomon, D. Bogdanov, C. Breyer, Solar driven net zero emission electricity supply with negligible carbon cost: Israel as a case study for Sun Belt countries, Energy 155 (2018) 87–104.
[30] A. Tishler, J. Newman, I. Spekterman, C. Woo, Assessing the options for a competitive electricity market in Israel, Util. Pol. 16 (2008) 21–29.
[31] H. Yu, D. Pearlmutter, M. Schwartz, Life cycle assessment of an energy-economy nexus: the case of Israel and South Korea, Environ. Impact Assess. Rev. 69 (2018) 61–69.
[32] D. Huppmann, M. Gidden, O. Fricko, P. Kolp, C. Orthofer, M. Pimmer, N. Kushin, A. Vinca, A. Mastrucci, K. Riahi, V. Krey, The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): an open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development, Environ. Model. Software 112 (2019) 143–156.
[33] C. Orthofer, D. Huppmann, V. Krey, South Africa after paris—fracking its way to the NDCs? Front. Energy Res. 7 (2019) art-20.
[34] J. Rogelj, D. Huppmann, V. Krey, K. Riahi, L. Clarke, M. Gidden, Z. Nicholls, M. Meinshausen, A new scenario logic for the Paris Agreement long-term temperature goal, Nature 573 (2019) 357–363.
[35] S. Messner, L. Schrattenholzer, MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively, Energy 25 (3) (2000) 267–282.
[36] CBS, Projected Population Growth, Israel 2065, 2017 [Online]. Available: https://www.cbs.gov.il/he/mediarelease/doclib/2017/138/01_17_138t1.pdf.
[37] E. Argov, S. Tsur, A Long-Run Growth Model for Israel, Bank of Israel, Jerusalem, 2019.
[38] PUA, Report on Electricity Sector 2018, Public Electricity Authority, Jerusalem, 2018.
[39] World Bank, Commodities Price Forecast, 2019.
[40] EIA, Annual Energy Outlook, US Energy Information Administration, 2019.
[41] Ministry of Energy, Recommendations of Committee for Examining Natural Gas Policy in Israel, Ministry of Energy, Jerusalem, 2018.
[42] IEA, World Energy Balances, International Energy Agency, 2019.
[43] L. Galo, Long Term Forcast for Electricity Demand in Israel, Bank of Israel, Jerusalem, 2017.
[44] EPA, Global Greenhouse Gas Emissions Data |Greenhouse Gas (GHG) Emissions, US EPA, 2014.
[45] Ministry of Energy, Energy Sector Development Targets for 2030, Ministry of Energy, Jerusalem, 2020.
[46] PUA, Increasing the Renewable Energy Goals in Power Generation 2030, Power Utility Authority, 2020.

[47] BOI, Bank of Israel, 1 June [Online]. Available: https://www.boi.org.il/en/Markets/Pages/ForeignCurrency.aspx, 2019.
[48] R.S. Pindyck, The social cost of carbon revisited, J. Environ. Econ. Manag. 94 (2019) 140–160.
[49] International Monetary Fund, The Economics of Climate Change, 2019.
[50] World Bank, World bank commodities price forecast (nominal US dollars) [Online]. Available: http://pubdocs.worldbank.org/en/598821555973008624/CMO-April-2019-Forecasts.pdf, April 2019.
[51] UNFCCC, Communication of long-term strategies [Online]. Available: https://unfccc.int/process/the-paris-agreement/long-term-strategies, 29 Sept 2020.
[52] J.H. Williams, R.A. Jones, B. Haley, G. Kwok, J. Hargreaves, J. Farbes, M.S. Torn, Carbon-neutral Pathways for the United States, AGU Advances, 2021.
[53] J. Rogelj, D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, M. Vilariño, Mitigation pathways compatible with 1.5°C in the context of sustainable development, in: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Chang, IPCC, 2018.
[54] BP, Energy Outlook, 2020 edition, BP plc, London, UK, 2020.
[55] R. Best, P.J. Burke, F. Jotzo, Carbon pricing efficacy: cross-country evidence, Environ. Resour. Econ. 77 (2020) 69–94.
[56] Z. Xin-gang, W. Ling, Z. Ying, How to achieve incentive regulation under renewable portfolio standards and carbon tax policy? A China's power market perspective, Energy Pol. 143 (2020).
[57] J.E. Aldy, R.N. Stavins, The promise and problems of pricing carbon: theory and experience, J. Environ. Dev. 21 (2) (2012) 152–180.
[58] D. Klenert, L. Mattauch, E. Combet, O. Edenhofer, C. Hepburn, R. Rafaty, N. Stern, Making carbon pricing work for citizens, Nat. Clim. Change (2018) 669–677.
[59] D.L. McCollum, V. Krey, K. Riahi, P. Kolp, A. Grubler, M. Makowski, N. Nakicenovic, Climate policies can help resolve energy security and air pollution challenges, Climatic Change (2013) 479–494.
[60] E.B. Barbier, Greening the post-pandemic recovery in the G20, Environ. Resour. Econ. 76 (2020) 685–703.
[61] World Bank Group, State and Trends of Carbon Pricing, 2020. Washington DC.
[62] C. Hepburn, N. Stern, J.E. Stiglitz, Carbon pricing" special issue in the European economic review, Eur. Econ. Rev. 127 (2020).
[63] M.R. Bloomberg, R.T. Aggarwala, Think locally, act globally, Am. J. Prev. Med. 35 (5) (2008) 414–423.
[64] M.E. Kahn, M. Kamiar, N.N.M. Ryan, P. Hashem, R. Mehdi, Y. Jui-Chung, Long Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis, National Bureau of Economic Research, 2019.
[65] R. Best, Q. Yue Zhang, What explains carbon-pricing variation between countries? Energy Pol. 143 (2020).