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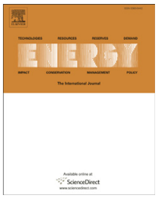

Assessment of the impacts of different policy instruments on achieving the deep decarbonization targets of island energy systems in Norway – The case of Hinnøya

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A B S T R A C T

Norway enjoys an electricity-dominant clean energy system with a high share of hydropower. The power and heating sectors are characterized by high penetration of renewables. But the transportation and offshore industries remain challenging to be decarbonized; therefore, it needs more exploration on cost-effective energy transition strategies. This study develops a long-term energy planning model, TIMES-Hinnøya, for the Hinnøya island in Norway and couples it with a detailed electricity system model with hourly time resolution, EnergyPLAN, to overcome the low temporal resolution limitation of the long-term energy planning model. The two models run iteratively. Using the model, five scenarios are designed to investigate the effects of key policy instruments on the energy transition. These scenarios assume the continuation of current climate policies, such as carbon tax on fossil fuels, preferential policies towards purchasing and owning electric vehicles, ban on new internal combustion engine (ICT) cars as of 2025, and the potential incremental carbon tax rate. The results illustrate that although absolute reduction occurs in all the scenarios, the goal of net-zero emissions by 2050 can only be achieved by forbidding the sales of new ICE cars, highlighting the importance of zero-emission vehicles in the future transportation system.

1. Introduction

Substantial mitigation of net global CO_2 emissions is required in the near or medium term to achieve the ambitious climate targets espoused by the Paris Agreement, necessitating a profound transformation of energy system and a massive volume of low-carbon investments (McCollum et al., 2018). In line with these climate targets, Norway has updated its Nationally Determined Contribution (NDC), aiming to cut the greenhouse gas (GHG) emissions by at least 50% and towards 55% compared to 1990 levels [1], and also set a carbon-neutral target by 2050 [2]. Norway is a country with a long, rugged coastline and thousands of islands. Investigating the least-cost decarbonization pathways of these archipelagic regions is essential for the country to reach its climate goals. Due to Norway's geographic conditions, the energy systems of these islands have some distinct characteristics. For instance, there are many small-scale hydropower stations distributed across the islands, whereas a large portion of their electricity consumption is supplied from the mainland grid. The grid is usually too weak to support additional demand, and the demand is too low to upgrade the grid. Grid upgrading and connection could be expensive for those distant islands, especially with a small population. Alternatively, exploiting indigenous renewable energy (RE) resources could help reduce the islands' energy self-sufficiency and contribute for mainland Norway low-carbon energy transition. In addition, as most of the GHG emissions come from the transport sector, investigating alternative transport technologies is critical for deep decarbonization. Several policy instruments have been enforced by the government such as CO_2 tax on fossil fuels and strong incentives for zero-emissions vehicles. Moreover, the government also enacted a ban on new fossil fuel car sales as of 2025. Prior studies on the decarbonization

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Nomenclature

RE	renewable energy
GHG	greenhouse gas
NDC	nationally determined contribution
ESM	energy system modelling
RES	reference energy system
ROR	run-of-river
MW	megawatt
HFO	heavy fuel oil
MGO	marine gas oil
ICE	internal combustion engine
ETS	emissions trading scheme
VAT	value added tax
ICT	incremental carbon tax
BAU	business-as-usual
BOC	ban on fossil fuel cars
IndE	increased independence of electricity supply
O&M	operations and maintenance
TJ	terajoule
Mvehicle	million vehicles
MEUR	million euros
Kton	thousand tons
Km	kilometers
EV	electric vehicle
PHEV	plugin hybrid electric vehicle
BEV	battery electric vehicle
HFCV	hydrogen fuel cell vehicle
HEV	hybrid electric vehicle
DICI	direct injection compression ignition
PISI	port injection spark ignition
PIDF	port injection dual-fuel
HPDI	high pressure direct injection
Ind-Pri	primary industry
Ind-Sec	secondary industry
Ind-Ter	tertiary industry
TP-Pri	private transport
TP-Pub	public transport
LD	light-duty
HD	heavy-duty
LCA	life-cycle analysis

of transportation focused on primary energy savings [3], GHG emissions reduction [4], and systems cost reduction [5] through the adoption of emerging transport technologies [3], incorporation of transport modal shift [5], and driving behavioral factors. Emphasis is given to the passenger car segment as it is the largest source of GHG emissions in road transportation [6]. Few studies on the investigation of policy instruments from whole system perspective such as carbon tax on fossil fuels [7], tax incentives on EVs and plugin hybrid electric vehicles [8], and CO_2 emissions standard on new cars [9]. In Ref. [6], the role of biomass for cross-sectoral integration and passenger car transport segment decarbonization in Sweden.

In the light of the stated energy transition challenges, it is worth investigating the effectiveness of current active- and new policy instruments. However, there is a knowledge gap regarding how the energy systems of these islands could transition under different policy scenarios. This paper attempts to fill this gap in a model-based techno-economic study, with an emphasis on the transport sector.

Energy system modelling (ESM) serves as a useful and widely adopted tool to conduct energy systems analysis. More specifically, the feasibilities of RE-based energy systems on islands have been assessed by means of various ESM tools. For instance, EnergyPLAN, developed and maintained by Aalborg University in Denmark since 1999, has been widely used for simulating regional and island energy systems [10,11]. [12] used EnergyPlan to analyze the economic competitiveness of solar PV and wind power for La Gomera island, a subtropic island in Spain [13]. used EnergyPLAN to design a 100% RE system for the Åland Island in Finland. A similar tool, H2RES, was developed as a dedicated planning tool for the analysis of islands' and isolated regions' energy systems [14]. [15] used H2RES to investigate different ways to increase the penetration of RE in the island of S. Vicente, Cape Verde. HOMER is another software used for hybrid system simulation and optimization [16]. Nevertheless, HOMER does not include innovative thermal technologies and is not suitable for a cross-sectional analysis [17]. Many of these studies aimed at achieving a high RE share or a 100% RE supply and integration of intermittent RE into the local power grid [18–20]. It was argued that optimal energy management using the smart grid approach is inevitable for the integration of more RE into the islands' energy system. This makes the islands pilots for RE development [21]. Despite these efforts, systematic research on the overall system modelling for a 100% sustainable energy transition on islands is limited [11]. For the assessment of the effectiveness of various policy instruments, long-term energy system models are deemed appropriate as they can cover a broader energy system. Nevertheless, the low temporal resolution in long-term planning models is a limiting factor for a realistic adoption of intermittent RE and to capture the demand and supply dynamics in the energy system. In this regard, the use of hybrid modelling approaches that soft- or hard-link different modelling tools offer an effective solution to overcome the technical and computational limitations of the individual models [17].

This study aims to investigate the effectiveness of different policy instruments on the energy transition pathways of a selected island in Norway. Hinnøya island, the largest island in the mainland Norway, is chosen for this study. Separate TIMES-Hinnøya and EnergyPLAN-Hinnøya models are developed and soft-linked in a unified modelling framework to alleviate their individual model limitations.

The remainder of this paper is structured as follows. Section 2 presents the hybrid modelling approach that connects the two different models. Section 3 presents the Hinnøya energy system and the various scenarios used for the analysis. Section 4 describes the detailed techno-economic parameters used in the model. Section 5 presents the scenario results and discussions, followed by conclusions and further discussions on the policy implications of the results in Section 6.

2. Methodology

As indicated in the introduction, this study takes a hybrid modelling approach that connects a long-term planning model, TIMES-Hinnøya, with a short-term economic dispatch model, EnergyPLAN. The long-term model is developed to encompass a variety of technological options with vintage tracking. It allows for a technology-rich representation of the various technological choices in the transport sector. EnergyPLAN features a higher temporal resolution and therefore enables to avoid overestimation of the integration of highly fluctuating or intermittent renewable energy sources such as wind and solar into the traditional power grid. Also, EnergyPLAN is suitable for the investigation of the impacts of increasing the share of RE on the entire energy system.

2.1. TIMES-hinnøya

TIMES (The Integrated MARKAL-EFOM System) is a generic partial equilibrium linear programming energy system model generator. It is a bottom-up technology-rich model suitable for detailed representation of technologies and the whole energy dynamics over a multi-period time horizon [22]. The overall objective function of the TIMES model, following the principle of partial equilibrium linear programming, is to satisfy the energy service demand with the minimum total discounted system cost at each time step over the entire planning horizon (i.e., the optimal energy-technology pathways). Thus, the model determines the optimal mix of technologies and fuels and the associated emissions and trading activities at each period. TIMES has been widely used for long-term energy system planning at global, national, and regional levels. For example, TIMES has been used to assess the global climate policies by modelling a multi-regional global energy system covering all primary energy sources from resource production to sectoral end-use energy conversion technologies and infrastructure requirements [23–25]. There are also extensive country-level applications. For example, Tattini et al. incorporated modal shift within the transport sector into TIMES-DK, a TIMES-based energy system model for Denmark to analyze the behavioral effect in achieving a sustainable transport sector [5]. Li et al. links TIMES-China and the Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS) to assess the co-benefits of air quality improvement under the low-carbon scenarios [26]. Kato and Kurosawa coupled TIMES-Japan with detailed sectoral models via soft-linkage to assess possible deep decarbonization scenarios in 2050 for Japan [27]. The TIMES-Norway model was developed by the Institute for Energy Technology (IFE) on the commission of the Norwegian Water Resources and Energy Directorate (NVE) [28]. TIMES has also been used in regional level applications in prior studies in Norway, such as investigating the prospects of forest-based bioenergy potential in Inland Norway [29].

In this study, a TIMES-Hinnøya model is developed to capture the entire energy system on the Hinnøya island. There is a particular interest in the detailed representation of the transport sector. Fig. 1 shows the reference energy system for the base year 2015. In the schematic diagram, energy commodities are marked by rectangle boxes, and technologies are indicated by rounded rectangular boxes. In 2015, approximately 90% of the total electricity consumption on the island was imported from the mainland grid. A more detailed statistical description of the reference energy system is provided in Section 3.

The objective function of the model is to minimize the total discounted system cost over the entire model horizon; in between 2015 and 2050, making investments and operational decisions at each period or year of interest at a given general discount rate. A variety of potential low-carbon technological options are considered to be adopted along the model horizon, in particular for the transport sector which is subdivided into private/public passenger, light-duty/heavy-duty freight, and ferries. A summary of these technological options and the associated parameterization in the model is provided in Section 4.

In energy system modelling, a coarse temporal resolution is a sensible simplification in a system with less variable renewable energy (VRE) sources or predominantly on fossil fuel-fired and nuclear plants [30]. This is because low temporal resolution models usually overestimate the amount of demand met by fluctuating renewables (such as wind and solar) as the share of VRE sources increases [31]. The TIMES modelling framework features a flexible definition of sub-annual time slices [22]. Thereby the diurnal variation due to peak and off-peak hour demands can be captured. Theoretically, introducing a total of 8760-h time slices within one year is also possible, but it could create computational intractability and a long computer running time. Several solutions have been proposed to tackle the problem. Pina et al. proposed a soft-linking approach that connects TIMES and EnergyPLAN [32] to reflect the impacts of wind power integration better. This study also follows the same approach to couple the TIMES-Hinnøya model and the EnergyPLAN-Hinnøya model to capture different dynamic characteristics of the Hinnøya energy system.

2.2. Soft linking TIMES and EnergyPLAN

EnergyPLAN has been commonly employed to simulate operations and energy balances in the energy systems on an hourly basis. The tool has been developed and maintained by Aalborg University in Denmark since 1999 [10].

Combining two or more different types of energy system models has been explored in prior studies [32–35]. For instance, it can be done in a one-directional manner to crosscheck the technical appropriateness of the optimized power system results arising from an energy system model [34]. Alternatively, a bi-directional iterative approach allows long-term energy systems models to iteratively interact with short-term economic dispatch models [32]. In this study, the bi-directional approach is used. The schematic diagram of the modelling framework is shown in Fig. 2.

TIMES-Hinnøya features horizontally and vertically integrated energy commodities and a detailed description of various technologies on both the supply and demand sides. Transportation is represented in a detailed fashion. It is employed to optimize the energy system over the model horizon. The key outcomes of the TIMES-Hinnøya model results are new investment capacities of various energy technologies, which in turn are the inputs to the EnergyPLAN-Hinnøya model run. For instance, the required electricity grid interconnection capacity may be smaller in the TIMES-Hinnøya model run than in the EnergyPLAN-Hinnøya model run because the latter has a higher temporal resolution. EnergyPLAN performs hourly simulation over a year and is capable of capturing additional technical constraints such as RE penetration and the associated storage capacity needed to balance the residual hourly load variation. These results are then used to update the TIMES-Hinnøya model, which in turn attempts for new solutions until no new capacity investments is required for system balancing. These iterations are performed exogenously until the technology mix results converge in all milestone (or model investments decision) years.

3. The hinnøya energy system and scenarios

Hinnøya is mainland Norway's largest island and is located in northern Norway. It has a population of approximately 32,700 inhabitants and encompasses an area of 2204 km^2. The location and geography of the Hinnøya island is shown in Fig. S1, in the supplementary information (SI). It is located completely within the electricity market region NO4 of Nord Pool, the largest electricity market in the World. More than 90% of the electricity is imported from the mainland via NO4. The remaining electricity demand is covered by the small-scale hydropower plants on the Island itself.

3.1. The reference energy system

The reference energy system (RES) consists of energy supply, energy conversion, and distribution technologies, end-use

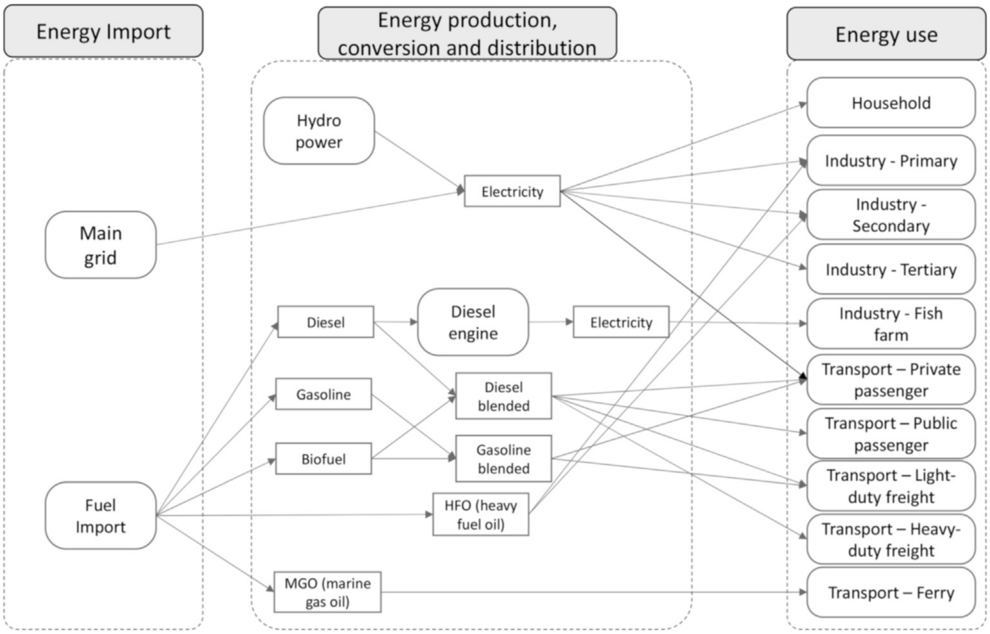

Fig. 1. The reference energy system of the TIMES-Hinnøya model.

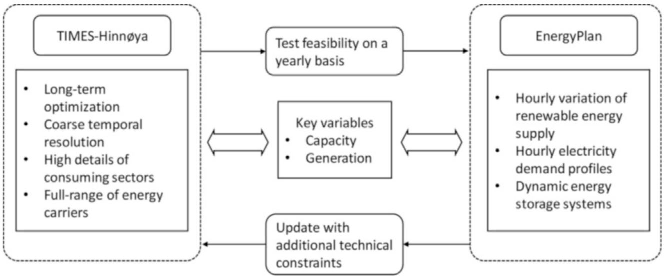

Fig. 2. Schematic diagram of linking the TIMES-Hinnøya and EnergyPLAN-Hinnøya models.

technologies, and service demands. It is used as a reference system in the TIMES-Hinnøya model for the assessment of various alternative future energy development scenarios. All the energy technologies and the energy flows in the RES are illustrated in Fig. 1. It is worth mentioning that fish farms are included in the primary industry sector and ferries in the transport sector. In addition to electricity imports, other energy carriers such as oil products and biofuels are represented as imported energy commodities.

The RES data is presented in Table 1. The total installed capacity of run-of-river (ROR) hydro power plants is 18 MW.

The main energy demand sectors include residential, primary, secondary, tertiary, and transportation sectors. Residential is the largest energy-consuming sector on the island, followed by transport. It is noteworthy that electricity is the most used energy commodity in the residential sector, both for electricity-specific applications and heating. Hydropower is the main source of electricity in Norway, and there are little or no GHG emissions from power generation in Norway. Transportation and offshore industries are the primary sources of GHG emissions in Norway, and so are in Hinnøya. In this regard, decarbonization of transportation using zero-emissions vehicles is important to realize the net-zero emission targets of Norway. The detailed representation of the transport sector by application and fuel type is shown in Fig. 3 [36]. Although the market penetration of EV shows a remarkable growth in Norway, the total electricity consumption in the transport sector is only 1.6 TJ and accounts for a very small share of the total energy demand in transportation, which is dominated by conventional internal combustion engine (ICE) vehicles.

3.2. *Scenario description*

The scenarios depict the various possible future events with regards to the deep decarbonization of the Hinnøya island energy systems and policy instruments that should be accounted for when designing the optimal configuration and evaluating technological potential. Realizing the targeted energy transition also strongly depends on the applied regulatory- and market-based policy instruments. It is therefore of great significance to assess the potential effects from current- and future alternative policy instruments. In the light of this, the main research questions that form the

Table 1
Energy supply and demand by sector in Hinnøya in 2015 (RES).

Commodity	Supply (TJ)	Energy sector	Demand (TJ)
Hydropower generation (ROR)	260	Residential use	1528
Imported electricity – main grid	2455	Primary industry	224
Diesel	673	Secondary industry	267
Gasoline	243	Tertiary industry	744
MGO	17	Transport	991
Biofuel	32		
Firewood	192		

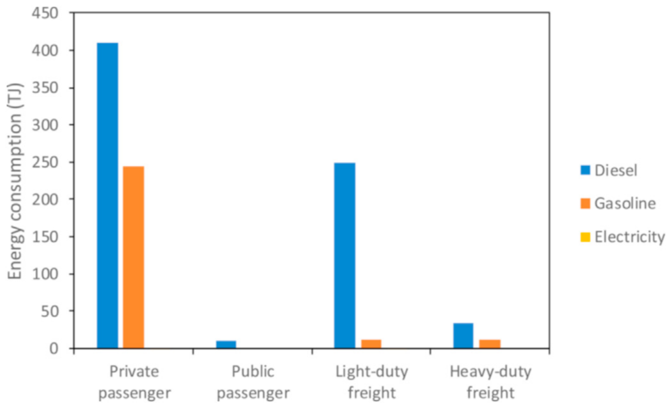

Fig. 3. Fuel consumption in the transport sector.

scenarios are: (1) What would be the future emissions of the Hinnøya island energy system if the current low-carbon policies continue in Norway; (2) What are the additional incentives, if any, required to realize a zero-emissions energy system in Hinnøya island.

Approximately 80% of the total GHG emissions in Norway are covered under the emissions trading scheme (ETS). As a cross-sectoral measure, CO_2 taxes have been introduced in Norway since 1991 on a variety of carbon-contained energy carriers from oil products to natural gas [2]. As of 2020, the CO_2 tax was increased by 5% in real terms to a standard rate of approximately 545 NOK/tonCO_2, equivalent of approximately 50 €/tonCO_2. There is also a minimum 24.5% biofuels blend requirement in road transport such as biodiesel and bioethanol with the conventional transport fuels, of which 9% is advanced biofuels.

The strong incentives for zero-emission vehicles put Norway at the vanguard in terms of electric vehicles (EV) ownership per capita. Both batteries EVs and fuel cell cars are exempted from the value added tax (VAT), the motor vehicle registration tax, the traffic insurance tax, and the re-registration tax. Plugin hybrid electric vehicles (PHEVs) owners can get preferential tax deductions if they meet certain standards such as a minimum electric driving range. In addition, in 2016, Norway announced that a ban on the sales of petrol and diesel cars would be enforced by 2025, which is a strong incentive for the market penetration of zero-emissions vehicles.

In this study, five distinctive scenarios are designed and presented in Table 2. The business-as-usual (BAU) scenario assumes the current policies to remain active in the years to come. The BOC scenario is identical to the BAU scenario but assumes a ban on new fossil fuel car sales in the passenger car segment after 2025. The incremental carbon tax (ICT) scenario is also identical to the BAU scenario, but it assumes an increasing carbon tax from the current level to 2000 NOK by 2030. The fourth scenario (BOC + ICT) assumes a more stringent situation where the BOC and ICT scenarios are combined together. The fifth scenario, IndE, assumes a 50% lower electricity import by 2050 compared to the BAU scenario.

The exogenous demand projection is the same for all scenarios between 2020 and 2050, as shown in Fig. 4. Future energy demand growth in the residential sector is estimated based on the population growth forecast of SSB (Farstad, 2018) and based on GDP growth assumption in primary (Ind-Pri), secondary (Ind-Sec), and tertiary (Ind-Ter) sectors. The transport service demand projection is based on the national transport model of Norway (Madslien et al., 2019). In line with the classification of transport sectors, mobility demand is divided into private transport (TP-Pri), public transport (TP-Pub), and LD and HD freight transport (TF-LD and TF-HD).

4. Techno-economic data assumption

In this section, the techno-economic data of the assumed technologies are presented. This study focuses on the transport sector and the power supply system of the Hinnøya energy system.

4.1. Transport

As illustrated in the RES analysis, transport is the main source of GHG emissions in the Hinnøya island energy system. Thus, replacing the current conventional fleet with a zero-emission fleet or low-carbon fleet is key to achieving the climate targets of Hinnøya Island and Norway at large. The assumed zero-emission vehicles and low-carbon vehicle transport technologies are summarized in Tables 2–4 [5,29]. In the passenger car transport segment (Table 2), a number of low-carbon technologies are included: conventional diesel/gasoline engine vehicles with biofuels blend, battery electric vehicles (BEV), plugin hybrid electric vehicles (PHEV), and hydrogen fuel cell vehicles (HFCV). The vehicles are classified by size (small, medium, and large) and driving range (short, medium, and long). The key vehicle parameters such as fuel economy and capital and O&M costs are also presented. The key parameters for public passenger and freight vehicle technologies (light-duty and heavy-duty) are summarized in Table 3. The average lifetime for passenger cars is assumed thirteen years, and for the freight, it is seven years. The assumed range of capital costs is due to the assumed future technological advancement of zero-emission vehicles.

In the ferry transport segment, the competing technologies in the model are low sulfur MGO ferry, LNG-propelled vessels with three different types of gas engines (port injection spark ignition (PISI), port injection dual-fuel (PIDF), and high-pressure direct injection (HPDI)), and electric ferry with onboard battery (Table 4).

4.2. Renewable energy supply

Hydropower and wind power are the considered power solutions on the Hinnøya island. The existing ROR hydropower has a

Table 2
Scenario description.

Scenario name	Short name	Description
Business as usual	BAU	Continuation of current policies, no more other policies, CO_2 tax rates remain the same throughout 2050 as in 2020
Ban on new conventional car sales from 2025	BOC	Implementing the ban on the sale of new conventional oil-combusting cars as of 2025, other policies and parameter settings are the same as in BAU
Incremental carbon tax	ICT	Increasing carbon tax incrementally from 545 NOK/ton in 2020 to 2000 NOK/ton in 2030
Ban on new conventional car sales and incremental carbon tax	BOC + ICT	Combining the ban on new fossil fuel cars after 2025 and the incremental carbon tax rate
Increased independence on electricity imports	IndE	Achieve a certain degree of local electricity supply and reduce electricity import by 50% in 2050

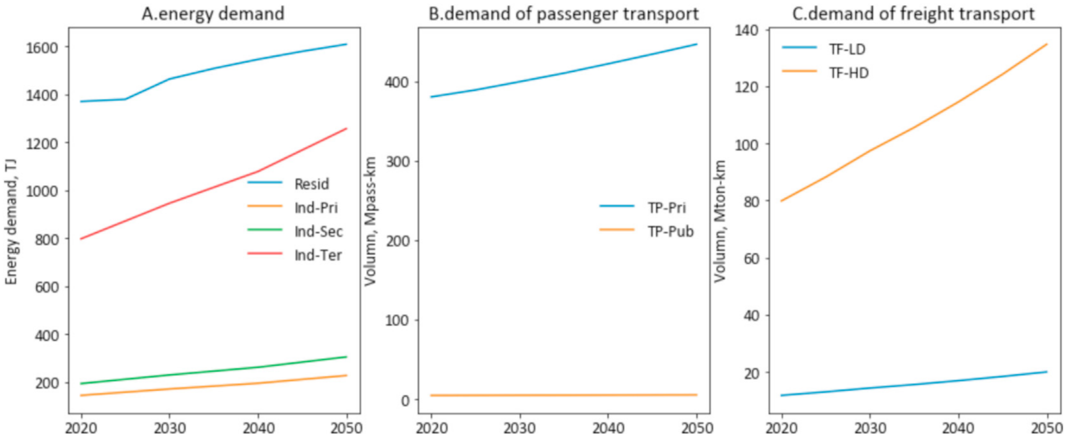

Fig. 4. Service demand projection by sector.

Table 3
Techno-economic data for private transport technologies.[1]

Technology	Fuel	Fuel economy [1] (Mvehicle-km/TJ)	Capital cost (MEUR/kvehicle)	O&M cost (kEUR/kvehicle*km)
Diesel engine - cars	Diesel biodiesel blended	0.17–0.53	24.21–56.00	0.03–0.06
Gasoline engine - cars	Gasoline bioethanol blended	0.13–0.41	23.54–55.91	0.02–0.06
BEV – cars	Electricity	1.06–1.90	23.77–50.14	0.02–0.07
HFCV - cars	Hydrogen	0.74–1.34	64.62–105.4	0.03–0.06
PHEV diesel – cars	Diesel	0.24–0.45	36.12–56.12	0.03–0.08
	Electricity	1.06–1.90		
PHEV gasoline - cars	Gasoline	0.19–0.34	35.12–56.03	0.03–0.08
	Electricity	1.06–1.90		
HEV – diesel	Diesel	0.22–0.71	26.14–64.57	0.03–0.05
HEV - gasoline	Gasoline	0.20–0.61	25.42–63.73	0.03–0.05

Data sources [29,37]:

Table 4
Techno-economic data for the public passenger and freight transport technologies.

Technology	Fuel	Fuel economy (kvehicle-km/TJ)	Capital cost (MEUR/kvehicle)	O&M cost (kEUR/kvehicle*km)
Diesel engine - buses	Diesel biodiesel blended	46.90–80.40	197	0.2
BEV – buses	Electricity	139	442	0.2
HFCV - buses	Hydrogen	83	787	0.3
Diesel engine - trucks	Diesel biodiesel blended	70–145	97–123	0.41
BEV - trucks	Electricity	310–417	207–246	0.2
HFCV - trucks	Hydrogen	177–240	338–394	0.3

Data sources [29,37]:

capacity of 18.35 MW. The remaining hydropower potential is estimated to be 20 MW, mostly small capacity plants. The coastal area has a favorable onshore and offshore wind power potential, and both are considered in the model. The key techno-economic parameters are presented in Table 5. The cost ranges shown in Table 5 cover the cost variations across the whole life of each technology (see Table 6).

The offshore wind turbines are normally larger in size compared to onshore wind turbines due to the stable and strong wind speed. It also has a higher capacity factor. Nevertheless, the capital costs are higher than onshore turbines. On the basis of the tower foundation, there are different types of offshore wind power technology: gravity-type, monopile, jacket-pile, tripod, and suction caissons. Monopiles have been dominating used in offshore wind

Table 5
Techno-economic data for the ferry transport technologies.

Technology	Fuel	Fuel economy (kvehicle-km/TJ)	Capital cost (MEUR/vehicle)	O&M cost (MEUR/vehicle/yr)
DICI engine	MGO	2.81	6.5	0.227
PISI engine	LNG	2.18	7.15	0.250
PIDF engine	LNG	2.81	6.82	0.239
	MGO			
HPDI engine	LNG	2.81	7.47	0.262
	MGO			
Electric engine	Electricity	6.3	10.82	0.379

Data sources [38,39]:

Table 6
Techno-economic parameters of the hydropower plants and wind turbines.

Technology	Type	Capacity factor	Capital cost (MEUR/MW)	Fixed O&M cost (MEUR/MW)	Variable O&M cost (MEUR/TJ)
Hydropower	ROR	0.53	1.25—1.57	0.0125	0.0176
Wind power	Onshore	0.32	0.92—1.46	0.011—0.026	0.0003—0.0012
Wind power	Offshore	0.47	1.35—2.22	0.032—0.06	0.0006—0.0012

Data sources [36,40]:

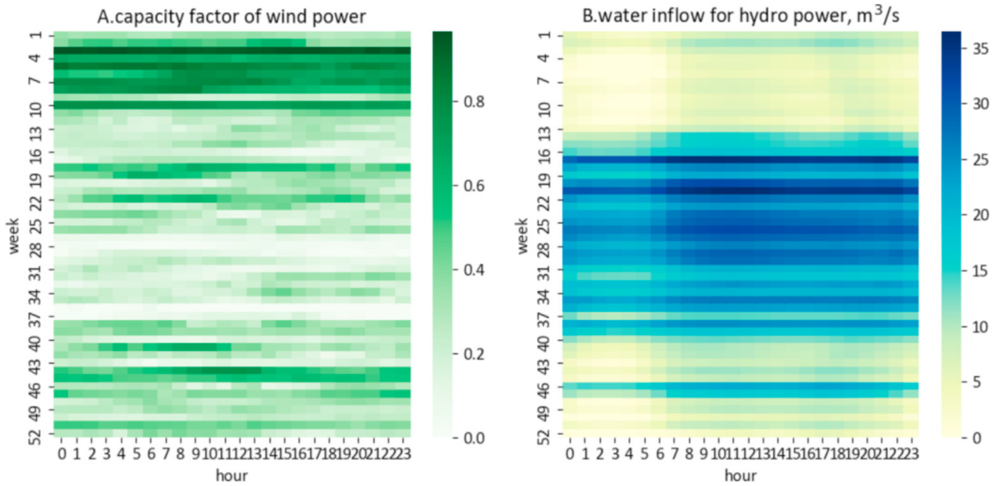

Fig. 5. Diurnal variation of water inflow and wind turbine capacity factor over a year.

turbines, representing 73.5% of the total global market [41]. The type of foundation used depends mainly on water depth and seabed conditions. Most offshore wind farms employ fixed-foundation wind turbines in relatively shallow water. Considering all the aforementioned factors and the demand size, the turbine size is assumed to vary from 50 to 150 kW for both onshore and offshore wind turbines.

The average historical water inflow data of various small-scale hydropower plants on the Hinnøya island is used for modelling purposes [42]. Likewise, the hourly wind power production data of the nearest wind farm to the Hinnøya island is used (with a total capacity of 32.5 MW) [36]. Fig. 5 presents the weekly average data of wind capacity factor (Panel A) and water inflow (Panel B) across 24 h. The annual average capacity factor of the wind farm was 0.33 in 2018, which is very close to the country-wide intermediate level [36]. It is found that wind and hydro both show higher significant seasonal variation rather than diurnal variation.

5. Results and analysis

In this section, in the light of the applied data assumptions, the model simulation results are presented for all scenarios. The energy supply mix, total CO_2 emissions, and the electrification rate in the transport sector are some of the key results presented in this section.

5.1. Energy supply mix

The energy supply mix results are presented in Fig. 6. The energy supply mix is essentially dependent on the available technologies, energy demand growth, and other exogenous assumptions applied in the model. The result shows that the baseline scenario (BAU) has the highest growth rate in energy supply. The total energy supply in the BAU scenario increases by 22% between 2020 and 2050, at an average annual rate of 0.6%. In the BOC + ICT scenario, the energy supply increases by only 0.4% in between 2020 and 2050, as it assumes the most stringent climate policies. The ban on new conventional car sales and the incremental carbon tax also stimulate the transition towards electrification in transportation and offshore industries (such as fish farms). As a result, the total electric energy use in the BOC + ICT scenario is the highest compared to the other scenarios.

The BOC and ICT scenarios show a similar increase in total energy supply. This shows that the carbon tax is as strong as the new car sales ban in terms of the adoption of low-carbon technologies. Nevertheless, a strong response is noted when the two scenarios are enforced together. As a result, the BAU and BOC + ICT have the lowest and highest total energy system cost in the five scenarios, respectively. The most stringent policies, represented by BOC + ICT, add approximately 28% of the total cost relative to the no policy scenario. Increasing local supply of renewable energy, as indicated by INDE, leads to a roughly 12% cost increase on the supply side.

The carbon-intensive fossil fuels are entirely phased out after 2045 in the BOC + ICT scenario and show a lower share in the BOC and ICT scenarios by 2050. As opposed to these, the percentage of fossil fuels is much higher in the BAU and INDE scenarios, accounting for 15% and 16% in total energy supply in 2050, respectively. The use of biofuels is comparably more significant in the BOC and BOC + ICT scenarios, as the residual conventional car stocks still exist by 2050, and biofuel blending is found to be competitive with

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[1] The fuel economy of a vehicle shows the distance driven by the vehicle in thousand km per unit TJ of energy consumption. The operation and maintenance (O&M) cost is expressed as euro (EUR) per unit km driven by a vehicle. In the model, however, the variable cost represents the cost of aggregate number of vehicles, and we multiplied both the numerator and denominator by thousand as kEuro/kvehicle*km.

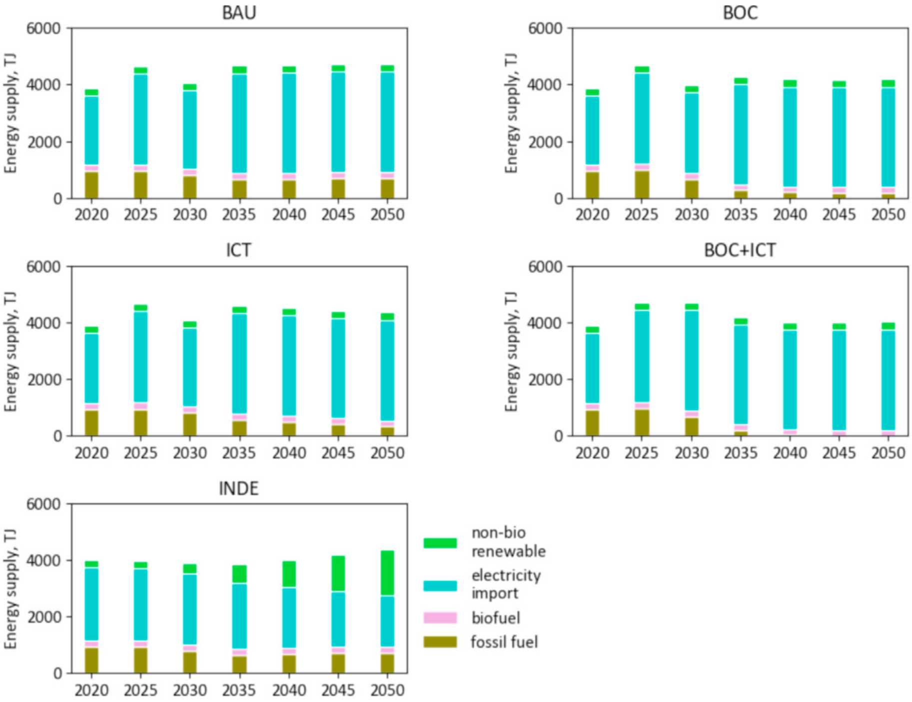

Fig. 6. Energy supply mix development between 2020 and 2050 in all scenarios.

conventional fuels. Nevertheless, electrification is found to be more favorable than biofuels under the assumed cost development. As a result, the electrification ratio is the highest in BOC + ICT scenario and increases from 70% in 2020 to 95% in 2050, whereas in the BOC scenario, the electrification ratio is approximately 80% in 2050. The BAU and INDE scenarios show the lowest electrification ratio.

The main source of electricity is the mainland grid in all scenarios except in the INDE scenario where the electricity imports are reduced to 50% compared to the BAU scenario in 2050. In this paper, electricity imports dependency is defined as the share of imported electricity in the total electricity supply. Except in the INDE scenario, all scenarios have a relatively stable level of electricity imports dependency in between 90 and 93%. The INDE scenario is designed as a special case to investigate the possibility of reducing electricity imports dependency and increasing the local renewable electricity generation instead.

Wind power is opted for in the model results to compensate for the reduced electricity imports. This is because the remaining hydropower potential is limited and insufficient to fully substitute electricity imports. Therefore, installing a wind farm at a larger scale is a more economical option. It is noteworthy that there are public environmental concerns on the development of onshore wind power in Norway, such as obscuring landscapes, endangering birds, and noise and visual pollution. The development of wind power in environmentally protected areas is not allowed, and stricter requirements are under discussion, which may result in higher costs for wind farm installation. Although these issues are not considered in the modelling process, it is worth further investigating in future research works. Reducing electricity imports dependency is a common issue during island energy system planning. In most cases, developing domestic renewable energy is a viable solution both economically and environmentally. Nevertheless, selecting the most suitable technology needs to include all multi-faceted concerns. The engagement of local municipalities and inhabitants is of great importance during the planning stage and project appraisal process.

5.2. CO_2 emissions

Policy incentives play a critical role in realizing deep decarbonization of the Hinnøya island energy system. The CO_2 emissions is shown in Fig. 7 for all scenarios. Generally, the CO_2 emissions are declining in all scenarios, albeit at significantly different paces. The BAU and INDE scenarios follow nearly the same trajectories. This is due to the similarities in the parameters pertaining to emissions between the two scenarios. Also, in these two scenarios, the CO_2 emissions drop is substantial between 2025 and 2035 and then remain stable afterward. This is due to the cost assumptions attributed to technological advancement that led to a low-carbon transition in specific sectors at a lower cost. Transportation, such as freight, is more costly to decarbonize, and thus the CO_2 emissions start to level off after 2035.

In the BOC + ICT scenario, which depicts the most stringent policies, zero CO_2 emissions are achieved. This demonstrates the impact of strong policy instruments in increasing the adoption of

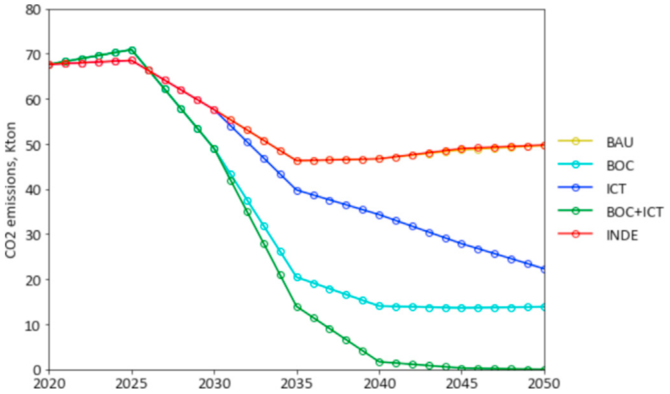

Fig. 7. CO_2 emissions development of the assumed scenarios in between 2020 and 2050.

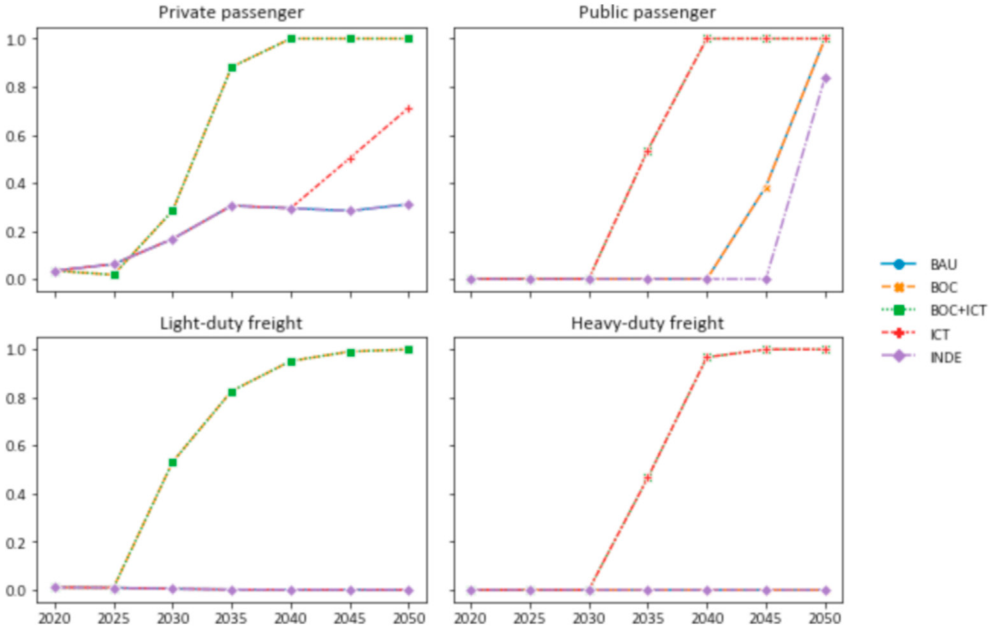

Fig. 8. The fraction of EVs in the total car fleet in the five scenarios.

low-carbon technologies that results in deep decarbonization of the Hinnøya island energy system as early as 2040. It is worth mentioning that no emissions are accounted for electricity imports as hydropower is the primary source (more than 96%) of electricity in Norway. Nevertheless, since the Norwegian grid is integrated with the thermal-dominated continental Europe grid via the Nordpool market, it would be more realistic if future works consider certain emissions associated with electricity imports in Norway at large.

In the BOC and ICT scenarios, distinctive CO_2 emissions patterns are found, as shown in Fig. 7, implying a significant difference in the assumed policy instruments. It shows that ban on new conventional car sales results in large emissions reduction from the private passenger transport segment, which is the largest emitting sector in the Hinnøya island energy system. Large emissions reduction is noted as early as 2035, and then after remain stable. The effect of increasing the carbon tax, ICT scenario, on CO_2 emissions reduction is less strong than the ban on new fossil fuel car sales. This is noted by the lower and gradual CO_2 emissions reduction of the ICT scenario. The CO_2 emissions in the ICT scenario are approximately 60% higher than that of the BOC scenario by 2050. Both scenarios are not able to fully abate the total CO_2 emissions by 2050, primarily due to the high cost of decarbonization in 'hard-to-decarbonize' sectors. Moreover, both BOC and ICT scenarios result in noticeable differences in terms of cumulative CO_2 emissions. The cumulative CO_2 emissions by 2050 are estimated to be approximately 882 Kton in the BOC + ICT scenario, 441 Kton in BAU scenario, 1410 Kton in ICT scenario, and 1084 Kton in BOC scenario.

In addition to the CO_2 emissions, air pollutants such as NOX and PM are also combustion products of fossil fuels in transportation and industries [43]. Thus, a more comprehensive analysis that considers the social damage cost of air pollutant emissions is therefore required to evaluate the actual benefits of zero-emissions vehicles and renewable energy supply in Hinnøya island. This is not included in the present study.

5.3. Transportation technology mix

Owing to the fact that transportation is the primary source of CO_2 emissions in the Hinnøya island energy system, investigating the adoption of low-emissions vehicles in transportation is at the core of this study. The transportation technology mix is shown in Fig. 8. Battery EVs and plugin EVs are the only dominantly used zero-emissions vehicles. This is due to assumed lower future costs for EVs and the relatively lower electric prices in Norway. Hydrogen fuel cell vehicles are not competitive due to the higher investment costs and hydrogen production and distribution costs.

The results show that in both BOC and BOC + ICT scenarios, the private passenger car segment is fully replaced by EVs in 2050. The BAU scenario also achieves a certain degree of EV penetration in the passenger car segment. The market penetration of EVs in the ICT scenario lies in between the BOC and BAU scenarios. The freight transport segment continues to use conventional vehicles, and EVs are not competitive due to the larger battery size and hence costs. The results are in general in line with prior studies.

The market competitiveness and adoption of EVs largely depend on the future technological advancement of the EV storage battery (mainly battery energy density and battery costs). In this regard, the model results are thus strongly dependent on the assumed costs. It is worth noting that low storage battery cost is critical for deep decarbonization of freight transport, ferries, and fish farms.

6. Conclusions and discussions

Achieving Norway's climate targets, reducing GHG emissions by 50–55% in 2030 and 90–95% in 2050 compared to 1990 level, requires deep decarbonization of transportation and industries in both mainland Norway and islands of Norway such as Hinnøya. This study develops a hybrid modelling framework that links a long-term energy planning model (TIMES-Hinnøya) and a short-term economic dispatch model (EnergyPLAN-Hinnøya) and investigates various deep decarbonization scenarios. The aim of the hybrid modelling framework is to overcome the inherent modelling limitation of the TIMES planning model, such as the low temporal resolution.

In this study, five distinct scenarios are designed to assess the impacts of various policy instruments on the total CO_2 emissions of the Hinnøya island energy system. The results show that, with the currently active policy instruments, the total CO_2 emissions will be reduced by 30% in 2050. However, the application of more stringent policy instruments such as the ban on new fossil fuel cars as early as 2025 will contribute to a 28% CO_2 emissions reduction in 2030 and an 80% reduction in 2050 compared to the 2020 level. The results also show that achieving zero emissions by 2050 requires the combined use of regulatory and market-based policy instruments such as the ban on new fossil fuel cars and incremental carbon tax.

In terms of per capita EV market penetration, Norway is at the vanguard. The strong incentives for EVs and low electricity prices in Norway are the main reasons for the high market share. This is in line with the results, where EVs fully replace conventional cars when the most stringent policy instruments are applied; ban on new fossil fuel cars sales and incremental carbon tax. Nevertheless, heavy-duty transport segments (such as freight transport and ferries) and offshore industries (such as fish farms) are more difficult to be electrified. This is due to the required large battery size and high battery costs, implying that substantial reduction in future battery costs and technological advancement (which lower battery energy density) are key for deep decarbonization of transportation.

More disruptive breakthrough in the relevant technologies is imperative for deep decarbonization. An in-depth cost-benefit analysis of emerging transport technologies such as hydrogen-based routes and large-size batteries should be performed. It is noteworthy that more benefits other than carbon emissions reduction should be included in the relevant analysis—for example, NOx and PM emissions and associated social damage costs of the air pollutants. The application of air-quality assessment models is relevant for such kind of analysis [44].

Increasing energy supply security through the development of diverse local renewable energy sources is vital for island energy systems. In this study, the possibility of reducing reliance on mainland electricity imports through the development of local small-scale hydropower and onshore wind turbines is explored. It is worth mentioning that the major assumptions regarding future developments of investment costs of wind turbines and EVs and electricity and fuel prices are highly uncertain. It should thus be noted that significant changes in these costs will have a considerable impact on the results. Also, CO_2 emissions associated with electricity imports are not considered. It is worth including it in future work for a more realistic result. This is because the electric generation mix is not 100% from renewable energy sources. Most long-term energy planning models, such as TIMES, are limited to a single impact category (GHG emissions) and fail to account for the upstream (supply chain) emissions such as air pollution, acidification, human toxicity, and other impact categories that are usually considered in life-cycle assessment (LCA) models. Thus, integrating LCA models and energy system models is critical for a realistic evaluation of alternative energy sources' role in climate change mitigation.

Credit author statement

Wenji Zhou: Conceptualization, Methodology, Investigation, Data curation, Writing, Writing – original draft, revision. **Dejene Assefa Hagos**: Conceptualization, Methodology, Data curation, Writing. **Sverre Stikbakke**: Conceptualization, Reviewing and editing. **Lizhen Huang**: Conceptualization, Methodology, Reviewing; **Xu Cheng**: Methodology, Reviewing and editing. **Erling Onstein**: Conceptualization, Reviewing and editing.

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.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2022.123249.

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