# The role of the discount rates in energy systems optimisation models

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## Abstract

*The selection of the social discount rate and the consideration of hurdle rates in energy systems optimisation models affect the creation of sound and comprehensive scenarios useful for energy modellers. Due to the lack of studies about the use of different discounting options in energy optimisation models, the goal of this paper is to fill that gap by establishing the foundations for a debate among energy modellers, policy-makers and stakeholders in this regard. So firstly, we introduced the concept of discount rates both social and technology-specific including a thorough literature review concerning figures, scopes and approaches. Secondly, two models, ETSAP-TIAM and TIMES-Norway, were used to assess the behaviour of the energy systems at different regionalisation levels, Europe and Norway respectively. Thirdly, we analysed the evolution of the electricity production mixes and system costs for both models and considering several values for the discount rates. Finally, results showed that the energy system is strongly affected by changes in the social discount rate. The lower the social discount rate is, the higher the renewable contribution. The social discounting exerts influence on capital intensive investments so it is quite important to look at the energy carriers pathways (fossil-renewable transition). This is what happens in the case of ETSAP-TIAM for Europe. Reversely, in the case of TIMES-Norway, as the electricity system is almost 100% renewable, it is important to take into account the hurdle rates of the technologies to enrich the competition by including their particular risks and barriers. In summary, we recommend using a value not higher than 4-5% for the social discount rate for the European countries as well as to include an exhaustive portfolio of hurdle rates for all the technologies included in the energy optimisation model.*

## 1. Introduction

The use of MARKAL/TIMES [1], a bottom-up energy optimisation modelling framework has been living an intense upsurge during last decade. This fact is founded on the countries' need to develop sustainable and long term policy goals, via roadmaps and strategic plans, which make possible ensuring the economic growth, combined with

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emission reductions and maximizing social welfare. In particular, TIMES models (the evolution of MARKAL) are used worldwide to develop energy plans and scenarios both at global level and country level. In Europe, most of the countries have developed their own national TIMES model [2]. Besides, International Energy Agency (IEA) is an important user/developer of this type of energy system models and collaborates in projects and consortiums spreading its use.

TIMES is a model generator for local, national or multi-regional energy systems, which provides a technology rich basis for estimating energy dynamics over a long-term, multiple period time horizon [1]. It is usually applied to the analysis of the entire energy sector, but may apply to study in detail single sectors. Nowadays, over 70 countries globally make use of the TIMES family of models [3, 4]. The modelling tools have been used for numerous studies, on a regional, national and global level, with various focus areas [5].

Even though TIMES modelling is a promising and interesting framework to manage prospective studies concerning energy systems, there are some weaknesses that should be analysed in depth. Prasad *et al*. [6] discussed the potential weaknesses of the energy models and they concluded that if the structure of a model is oversimplified results deviate from reality. One of the main issues detected in the community of the energy optimisation modellers, both in peer-reviewed papers and technical reports from projects, is the lack of sensitivity analyses and discussions concerning the discount rates.

The choice of the discount rates and the evaluation of its consequences in terms of technological preferences, sustainability and policy goals, involves a controversial issue. Some studies have brought into question this point: *why they chose that discount rate? It seems too low/high*. For instance, the Integrated Energy Policy Report (IEPR) [7] stated that "*apply inappropriately high discount rates to future fuel costs, thereby understating the impact upon consumers. The net result is a systematic undervaluing of non-fuel-intensive procurement alternatives, such as efficiency and renewables, and an increasing dependence on gas-fired generation*." As Ringer [8] remarks, the IEPR should recommend to discount future fuel costs at the 3% social discount rate used in ordinary activities, unless the investor-owned utilities can prove that these costs should be allocated to shareholders. So, we can observe that the choice of the discount rate entails problems. In particular, the selection of this value in the TIMES models is crucial, as demonstrated in this paper.

This work aims to review the literature on social discount rates, and also hurdle rates, from a TIMES modelling point of view. It has the purpose of enlighten the absence of references and the need of discussion in data selection as well as to point out the weakness of this type of models with respect to the uncontrollable parameters, such as the discount rates. To do so, the recognised worldwide ETSAP-TIAM model is used to analyse the European energy system and likewise the TIMES-Norway model is used to observe the consequences of using several discounting options at national level. Differences and similarities due to the regional approach are also discussed. Finally, some main conclusions and recommendations are pointed out.

## 2. Discount rates and hurdle rates

According to EC [9], the discount rate is the degree at which future values are discounted to the present. There are two approaches: financial discount rate and/or economic discount rate. They may differ, likewise that market prices may vary from accounting prices. Furthermore, the concept of social discount rate, in contrast to the financial discount rate, attempts to reflect the social view on how the future should be valued against the present.

The discount rate is used to adapt all costs and reimbursements to ‘present values’, so that they can be compared. Calculating the present value of the differences between the streams of costs and reimbursements provides the net present value (NPV) of an option. The NPV is the primary criterion for deciding whether government action can be justified [10]. The discounting factor ($D_t$) to calculate the *NPV* is given by:

$$D_t = \frac{1}{(1+r)^t}$$

(1)

where $r$ is the discount rate and $t$ is the time in years. In consequence, it is required to distinguish between the social discount rate and the financial discount rate in relation with the use of the discounting expressed in Eq. (1). The choice of social discount rates is usually a concern to the governments since they are entities which represent the entire society and its awareness (environment, moral principles, sustainability, economic growth, security, etc.). On the contrary, the financial discount rate is a concept to characterise the private investments which do not have the duty to consider the social concerns such as welfare or sustainability.

From a private point of view, the appropriate discount rate should represent the opportunity cost of what else the firm could accomplish with those same funds. If that means that the money could be used instead to invest in the private sector that would yield 5% and that is the next best alternative for using that money, then 5% would be the social discount rate [11].

Besides, the internal rate of return (IRR) is the discount rate that would give a project a net present value of zero so that the expected income perfectly balances the initial investment.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} = 0$$

(2)

Where the $C_n$ is the cash flow in a period $n$ and the $NPV$ function is given for $N$-integer (number of periods). In the private sector, hurdle IRRs are often used to test whether a proposal should go ahead. The riskier the project is, the higher the hurdle IRR [10].

A resulting IRR higher than the discount rate to be chosen is a good sign. However, no distinct value can be provided at which an IRR could be considered economically reasonable; instead an IRR should exceed the opportunity costs of capital, i.e. the interest rate one might generate through alternative investments, or be higher than an applicable social discount rate [12]. It is then defined the concept of Minimum Acceptable Rate of Return (MARR), the minimum discount rate on a project a company is willing to accept before starting a project, given its risk and the opportunity cost of forgoing other projects [13]. MARR is the technical definition for the hurdle rate.

In addition, the choice of the discount rate is decisive since it involves risks and barriers implicitly considered, as discussed in the following section.

## 2.1. Overview

This section introduces the concept of discount rates from a TIMES approach. Our main hypothesis is that choosing the discount rate is crucial because slight variations in this value cause significant changes in the evolution of the energy system. To justify this premise, it is required to show the effects looking at the electricity production mix and the system costs.

The bottom-up models, such as TIMES, are based on an explicit representation of the technology portfolio and, at the same time, they take into account the costs of the energy system. Albeit they are comprehensive, these types of models are often weak when certain barriers are considered. Most models only make use of a combined approach by means of an adjusted discount rate. While some models do not even consider technology costs and energy prices, but instead use exogenous technology rates, other more advanced models took first steps towards considering barriers in more detail. The latter allows assessing which parameters influence the energy system. Still, even in the most advanced models, only a few of the observed barriers are explicitly considered. Furthermore, technology adoption is considered as a rational decision-making process, assuming perfect knowledge [14].

The usual way which some models reflect barriers is by assuming higher discount rates for the energy projects investments although other models include exogenous assumptions of the energy efficiency developments [15]. As discussed by Worrell *et al.* [16], these approaches lack thorough understanding of the relevant barriers and their effect on technology adoption.

Fleiter *et al.* [14] carried out a detailed analysis regarding the different types of barriers in several bottom-up models. Accordingly, the authors refer to the Intergovernmental Panel on Climate Change [17] who distinguishes four groups of barriers: lack of information, limited availability of capital, lack of skilled personnel and other barriers. Considering the work of Sorrell *et al*. [18], authors broaden the classification by establishing the following list of barriers: imperfect information, hidden costs (and benefits), risk and uncertainty, split incentives, access to capital and bounded rationality. As Fleiter *et al.* [14] remarks, TIMES/MARKAL models present a simple aggregated approach in which the barriers are modelled by assuming changes in the price elasticity, discount rate and other relevant technical parameters.

Concerning the social discount rate, this is a case where discounting for the very long term implies that a discount rate that declines over time is appropriate. According to HM Treasury UK [10], the risk assessment (as barrier) includes several critical factors such as the investment costs, the identification of possible risks, the lack of data and the possible responses to natural danger. Consequently, the main variables to consider are: imminent protection measures for natural areas, natural risk frequency or probability of disaster occurrences, information regarding historical regarding occurrences, technical and physical information, identification of one of the four ways of responding to identified risks (acceptance, avoidance, transfer or mitigation).

Furthermore, the discount rates should be considered from the perspective of the concern for which the specific project/technology is applied for. That is the reason behind the use of hurdle rates. As Anandarajah *et al*. [19] exemplifies in the case of using a 3.5% social discount rate, they include specific hurdle rates, 7%, doubled respect to the social rate. The social discount rate covers the social rate of time preference, which is society's pure time preference for consumption, plus the diminishing marginal utility of consumption as wealth increases. The intuition behind these different social discount and hurdle rates is as follows. On one side, the social discount rate describes situations in which markets work perfectly and it is considered appropriate that market criteria govern all (including social and government) decision-making. On the other side, hurdle rates –higher than social– are introduced to take into account market imperfections which impede investments among other barriers. Social rates are appropriate in cases when there are public or social reasons for undertaking investments or assessing costs, which supplement market concerns.

With regard to the mathematical approach, TIMES models compute for each region a total net present value (NPV) of the stream of annual costs, discounted to a predefined reference year. These regional discounted costs are then aggregated into a single total cost, which constitutes the objective function to be minimized by the model in its equilibrium computation [1].

$$NPV = \sum_{r=1}^{R} \sum_{y \in Y} \left(1 + d_{r,y}\right)^{REFYR-y} \cdot ANNCOST(r,y)$$

(3)

where $ANNCOST(r,y)$ is the total annual cost in region $r$ and year $y$; $d_{r,y}$ is the general discount rate; $REFYR$ is the reference year for discounting; $Y$ is the set of years for which there are costs, including all years in the horizon, plus past years (before the initial period) if costs have been defined for past investments, plus a number of years after the end-of-horizon where some investment and dismantling costs are still being incurred, as well as the salvage value; and $R$ is the set of regions of the model.

The annualized capital cost payments, minus salvage value, form the $ANNCOST$, i.e. this term includes a list of costs which are affected by the discounting except the salvage. As expressed in Eq. (3), the $NPV$ is interpreted, in the case of considering one single region r, as the regional objective function $OBJ(z,r)$:

$$OBJ(z,r) = \sum_{y \in \pm\infty} DISC(y,z) \times \left\{ \begin{matrix} INVCOST(y) + INVTAXSUB(y) + INVDECOM(y) + \\ +FIXCOST(y) + FIXTAXSUB(y) + VARCOST(y) + \\ +ELASTCOST(y) - LATEREVENUES(y) \end{matrix} \right\} - SALVAGE(z)$$

(4)

where the $DISC(y,z)$ is the discount factor referred to the beginning of the year $z$; $INVCOST(y)$ is the investment cost; $INVTAXSUB(y)$ are the taxes and subsidies attached to the investments; $INVDECOM(y)$ is the capital cost related to the decommissioning; $FIXCOST(y)$ are the fixed annual costs; $FIXTAXSUB(y)$ are the taxes and subsidies linked to the fixed costs; $VARCOST(y)$ are the variable annual costs; $ELASTCOST(y)$ is the cost resulting from the loss of welfare due to the reduction (or increase) of demands in a given run compared to the base run; $LATEREVENUES(y)$ represent the late incomes; and $SALVAGE(z)$ is the salvage value –the estimated resale value of an asset at the end of its useful life– for the entire end-of-horizon [20].

In the course of minimising costs with demand constraints, the optimal solution returns step-wise increasing supply curves in TIMES. The supply curves are built for both intermediate products and final energy/energy services demands. It is said that supply curves rank technology by economic merit order [21]. In other words, the consequence of minimising the objective function expressed in Eq. (4) is the creation of several supply curves which satisfy the exogenous energy services demands. The discounting is entered by means of the term $DISC$ which exerts influence on the costs separately. As we will discuss in this paper, the effect of choosing different discount rates is different depending on the technology characterisation and the specific cost analysed.

### 2.2. Discount rates in TIMES studies

The purpose of this work is to analyse the importance of the discount rates in energy optimisation models, such as TIMES, and to focus on the lack of discussion concerning the selection of one value instead of another. This section discusses existing studies which make use of different discount rates, hurdle rates, and the approach they use, as well as the way in which TIMES interprets them.

There are two main types of variables in TIMES model: endogenous and exogenous variables. The endogenous ones characterize elements of the energy system whereas exogenous variables represent elements not included in the system. The content of the two categories depends on the definition of the system boundaries.

Several exogenous variables, such as the potential of fossil resources, the availability of renewables, and the efficiency of the different technologies, have a strong influence on the behaviour of the system but they are not influenced by policies and measures. Other exogenous variables, such as the discount rate, the prices of energy goods, the efficiency of the devices available on the market, or emission standards, strongly depend on policies. The level of controllability of the system depends on the number and importance of the variables that are influenced directly or indirectly by the exogenous control variables [22].

The key group of exogenous assumptions regarding the bottom-up models is the characterization of technological pathways. Different assumptions on technical and economic developments of both existing and new technologies determine the future of the energy systems. The innovation is only partly controllable by means of supporting policies, while the deployment of new and more efficient technologies is more affected by long term policies on information, regulation, taking sustainability and economic growth as main incentives.

Another set of exogenous assumptions is the future development of the demand for energy, be it primary, final, useful or energy service. Several studies on statistics or sectorial analyses of macroeconomic indicators help making demand projections by using “drivers” such as population, households, GDP, etc. Furthermore exogenous price projections may include taxes and subsidies [22].

In particular, the discount rates considered in the TIMES modelling exercises are usually social discount rates (for the entire energy system) and, in some cases, if relevant, they also include hurdle rates for certain technologies. For instance, in the JRC-EU-TIMES model, the authors used both approaches [23]. Several global discount rates were used for the social discounting besides hurdle rates for specific technologies. Social discounting was used to reflect the valuation on well-being in the incoming years versus well-being in the long term. A social (global) discount rate of 5% was considered in that report. This figure represents a real discount rate and it is determined by two main concepts: the time preference for consuming and the expected change in the per capita consumption. The time preference denotes the rate at which individuals discount future consumption over present consumption (in a *ceteris paribus* situation). On the other hand, when the expectation of the per capita consumption increases, a lower marginal utility is assumed for the additional future consumption. In other words, the higher the discount rate, the lower the impact of the future extra costs. It is remarkable that social discounting affects all costs in the model, including operational costs.

In the same document [23], technology-specific discount rates were discussed for their implementation in the JRC-EU-TIMES model. It is agreed that the higher the hurdle rate, the higher the annual payments spread over the lifetime of an investment and consequently the higher the total cost. In addition, the hurdle rate affects only the investment costs so the impact is bigger for capital intensive technologies like nuclear and most renewable technologies. The authors considered different hurdle rates for the different technologies of each sector. For example, the centralised electricity production assumes 8%; the energy distribution 7%; the CHPs and large industries 12%; and other industries and commercial 14%. The residential sector assumes 17% of hurdle rate; all the freight transport 11%; and the passenger cars 18%. Main sources of data for the discount rates were the EU Energy Roadmap 2050 [24] and the PRIMES model documentation [25].

In Mallah and Bansal [26], a study concerning MARKAL models, the analysis was focused on the evaluation of the model's response to variations in input assumptions. This work assessed the following parameters: efficiencies of the electricity production technologies, availability factors, fuel prices, investment costs, discount rates and technology-specific discount rates (hurdle rates). The scope of the study was India, the horizon was 2045 and the reference year was 2005. These authors included variations in the social discount rate from 6.5% to 15% as well as a sensitivity analysis for the hurdle rates of several electricity production technologies (using 5%, 18% and 25%). Results showed that social discount rates had a crucial effect in the evolution of the entire energy system but the inclusion of hurdle rates was almost negligible. The main conclusion was that at lower global discount rates coal is the least preferred technology and correspondingly carbon emission reduction.

In addition, Kannan [27] evaluated the effects of the uncertainties in the low carbon policies included in the UK MARKAL model for the production of electricity. To do so, the author developed a portfolio of scenarios modifying the targets on $CO_2$ limits, the technology variants (no new CCS, no new nuclear, neither new CCS or nuclear, neither CCS, nuclear or advanced renewables) as well as testing low (3.5%) and high (15%) discount rates. In this case, the sensitivity analysis for the discount factors is focused on the social discount rates only. The hurdle rates are not considered. The main conclusion was that if appropriate policies were to be implemented to reduce the risk in investing in the low carbon technologies, a social discount factor of 3.5% scenario would bring the system cost down respect to the reference case (8%) and vice versa in the case of high discount rates.

Looking at other studies, Kannan and Turton [28] developed a detailed assessment of the nuclear policies in Switzerland by using the Swiss TIMES model. This work included a brief sensitivity analysis concerning the discount rates of the nuclear technologies. On one side, the authors modified the hurdle rate of the nuclear technology only (testing 6% and 10%) and, on the other side they changed the global discount rate of all the electricity production technologies, going from the 3% of the Base scenario to 6% and 10%. The effects of both strategies will be discussed later in accordance with our results.

Other works, related to TIMES models, have used different discount rates for the description of the energy system without further discussing the implications or implicit assumptions behind this choice. For instance, Hu and Hobbs [29] included a 5% social discount rate in the USEPA MARKAL model and they avoid establishing extra hurdle rates to evaluate the behaviour of the electricity generation technologies under pollutant-related policies. McDowall *et al.* [30], to evaluate the bioenergy in UK using MARKAL, considered a social discount rate of 3.5% assuming that this figure was in line with the HM Treasury UK. Schäfer and Jacoby [31] analysed the users behaviour of the UK transportation system by means of MARKAL and considering some hurdles rates for the vehicles. Besides, they carried out a sensitivity analysis with hurdle rates, 5%, 10%, 20%. Kannan and Strachan [32] evaluated the residential sector in UK using MARKAL and considered a 25% hurdle rate for end-use technologies. Besides, Kannan [33] worked on the time slices of the UK model considering a global discount factor of 10% to reflect the commercial UK market rates of return and 25% for advanced end-use technologies ($H_2$ cars, etc.) to reflect barriers. More recently, Kannan and Turton [34] assessed the electricity dispatch in the Swiss TIMES model using a social discount rate of 3%.

Other models present the same issues. For instance, Ystanes Føyn *et al.* [35] used 5% social discount rate to analyse the long-term evolution of the global energy system under climate policies with TIAM. Accordingly, similar studies using the Balmorel model were developed by Hedegaard *et al.* [36], using a 5% rate, and by Juul and Meibom [37], considering a 3% social discount rate.

If we broaden the scope to other types of methodologies, such as the Cost Benefit Analyses, hundreds of works arise. An interesting and complementary study for the selection of discount rates was developed by Bottero *et al*. [38].

# 3. Methodology

## 3.1. ETSAP-TIAM model

The TIMES (The Integrated MARKAL-EFOM System) model generator was developed by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency (IEA).

The TIMES Integrated Assessment Model (ETSAP-TIAM) is a global multiregional model of the TIMES model generator [39, 40]. In particular, ETSAP-TIAM considers a large scope: the world is divided in 16 regions and the time horizon goes from 2005 to 2100. In addition, ETSAP-TIAM includes a climate module with climatic equations which make it possible to assess scenarios related to the greenhouse gas emissions in the long-term. Some experiences using TIAM have emerged during the last years in Europe. For instance, the TIAM-UCL model has been used in several UK projects [41].

The main structure of the ETSAP-TIAM model is presented in [39] and it is mainly conformed by the following entities: energy supply sector (primary energy sources, resources potentials), energy trade (import/export of energy carriers among regions), energy transformation (processing of primary sources to produce usable energy commodities), energy conversion (electricity production technologies), energy consumption sectors (end-use sectors such as residential, industry, transport, etc.) and emissions (GHG emissions factors and some others).

### 3.1.1. Power sector

In ETSAP-TIAM, electricity (high voltage) can be produced by a portfolio of technologies according to their particular characteristics (costs, efficiencies, availability factors, etc.). There is an important distinction between the two main types of technologies: existing and new. The “existing” technologies are those that were pre-installed in the reference year, 2005, whereas the “new” technologies are future (beyond 2006) technological options in such a way that if energy services demands increase, new electricity production plants should be installed to satisfy the extra needs. This will happen along with the retirement (due to their lifetime) of the “existing” technologies. As the emphasis of this work is focused on Europe, ETSAP-TIAM regions named WEU and EEU will be considered[†]. Theoretically, this simplifies the analysis to the electricity production in

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[†] WEU (Western Europe) includes Austria, Belgium, Denmark, Finland, France (with Monaco), Germany, Greece, Iceland, Ireland, Italy (with San Marino and Vatican), Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland (with Liechtenstein) and UK. Besides, Gibraltar and Greenland are also included. EEU (Eastern

Europe instead of the total energy system (the world). From a methodological point of view, the runs are managed for the 16 regions of the model all together. This is due to the requirement of avoiding imbalances throughout the electricity trade amongst the WEU & EEU and the adjacent regions.

The existing and new electricity production processes included in ETSAP-TIAM are described in [39:41]. The existing ones are mainly common technologies using coal, oil, natural gas, hydro, biomass, nuclear (fission), wind (onshore), geothermal, solar (PV and thermal) and some CHPs. The new technologies considered are basically more efficient options than the existing ones (improvements in designs, new components, etc.) and/or advanced technologies, i.e. new technological pathways within the same branch, for instance, third-generation reactors in nuclear fission or air blown coal IGCC plants.

### 3.1.2. Discount rates in ETSAP-TIAM

In the ETSAP-TIAM model, the social discount rate used as reference is 5%. This value is considered under the basis of a conservative assumption: ETSAP-TIAM is a global model and uncertainties coming from the different regions are different. It is not the same base risk for Africa as for Western Europe when the model invests in different technological options. In the most developed regions it seems reasonable to have lower discount rates, around 3%, while in other regions, due to the risks and uncertainties, the social discount rate should be higher. For that reason, and in line with other international optimisation models like PRIMES or MERGE, ETSAP-TIAM assumes 5%.

In addition, ETSAP-TIAM includes a set of technology-specific discount rates for technologies in different regions. For instance, it includes hurdle rates for several transport technologies from 10% to 15% depending on the case as well as 15% for investments in new residential and commercial technologies and 10% in heating and industrial processes. In the case of the EEU region, the transport options involve hurdle rates going from 17.5% to 25%, the residential and commercial 25%, the investments in heating measures 10% and the industry uses 17.5%. For the convenience of this work, the analysis of technology-specific hurdle rates on electricity production technologies has been disaggregated and it is not included in the base case of ETSAP-TIAM.

To summarise, ETSAP-TIAM model uses a social discount rate of 5% and a list of hurdle rates for the investments in sectorial technologies but excluding the electricity generation. This conforms to the Business as Usual (BaU) scenario for ETSAP-TIAM model.

## 3.2. TIMES-Norway model

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Europe) includes Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Slovakia, Slovenia and Yugoslavia.

The TIMES-Norway model was developed by the Institute for Energy Technology (IFE) on commission of The Norwegian Water Resources and Energy Directorate (NVE). The development began in 2008 [42]. TIMES-Norway, like most of the TIMES models, encompasses a technology-rich basis for estimating energy dynamics over a long-term, multi-period time of the Norwegian energy system. It is characterised by its high time resolution and its modelling horizon goes from 2010 to 2050. The base year is 2010, so all prices and costs are referred to this year [43]. The structure of the TIMES-Norway model is illustrated in Figure 1.

(FIGURE 1)

The energy services demands, the techno-economic characterisation of the technologies as well as the energy resources costs, availability and the social discount rate are given exogenously. Transmission and distribution include high and low voltage grids (losses in the grid are included), as well as district heating. Energy efficiency measures are included [44]. Transportation by passenger cars is modelled with 17 different technologies, including hybrids, battery electric vehicles, fuel cell vehicles, plug-in hybrids and internal combustion engine vehicles. The TIMES-Norway model was initially developed in order to perform mid-term analyses and to integrate the Nordic Power Market Model (EMPS) [45]. For that reason, TIMES-Norway presents a thorough temporal disaggregation (260 time slices).

### 3.2.1. Power sector

An overview of all the electricity production technologies is given in Table 1. The potentials are also included. Modelling of hydro and wind power technologies are highly detailed by means of time slices which define the load profile curve of the electricity system and the availability factors of the resource. Due to political reasons, no nuclear or coal plants are included as possible future investments. In the case of the Natural Gas Combined Cycle (NGCC) plant, there is only one, a 420MW-plant placed in Kårstø, but it was closed in 2014. Nevertheless, the possibility of new natural gas plants is open by means of new NGCC processes which include $CO_2$ capture. It is assumed that the $CO_2$ is transported by pipeline, and the costs of transport and storage are included. This description may be seen in more detail in Lind *et al.* [43] and Lind and Rosenberg [42].

(TABLE 1)

The hydropower technologies are currently generating between 95 and 99% of the electricity produced in Norway, of which reservoir (dams) counts for approximately 70%, being the rest run-of-river. Electricity production in reservoirs is divided between existing plants, new large plants and plants for increased capacity. Run-of-river hydropower production is modelled similarly to wind power [43].

### 3.2.2. Discount rates in TIMES-Norway

In TIMES-Norway, the social discount rate considered for this work is 5%. The Norwegian Ministry of Finance [46] assumes as reasonable for Norway a social discount rate of 4% but it is not clear which risks are included in that figure. For that reason, we have decided to use 5% as in large free-risk projects. It seems reasonable to consider the new electricity production plants comprised in this group.

TIMES-Norway also includes technology-specific rates for several energy efficiency measures (insulation roof, insulation floor, insulation wall, front doors, windows, tightening, water savings, new water heaters, heat plant, ventilation in heating systems, control and regulation, energy management and user information). The hurdle rate for all these measures is 10%. Likewise, Norwegian biodiesel production processes include a hurdle rate of 10%.

In summary, the Business as Usual (BaU) scenario in TIMES-Norway includes a social discount rate of 5%, and technology-specific hurdle rates for energy efficiency measures.

# 4. Scenario implementation

This section describes the list of scenarios used both in ETSAP-TIAM and TIMES-Norway models for different cases: using several social discount rates and hurdle rates.

## 4.1. ETSAP-TIAM scenarios

As observed in several studies, the use of different social discount rates influences the entire energy system throughout the different economic sectors. Consequently, these values should be selected carefully. According to the literature review, TIMES modelling works use discount rates ranging from 3.5% [34] to 15% [26]. As the purpose of current work is to analyse in depth the consequences of selecting different discount rates, we selected a wide set of social discount rates in ETSAP-TIAM (see Table 2).

(TABLE 2)

Likewise, we introduced different hurdle rates in the electricity generation sector in order to observe the sensitivity to changes in the technology-specific discount rates. To do that, we used Oxera [47] as main reference. Two scenarios were included, one with high values and other with low values. Both scenarios are described in Table 3.

(TABLE 3)

In Table 3, hurdle rates for a wide set of technologies are presented. As ETSAP-TIAM model also includes more technologies, it was necessary to find the hurdle rates for the rest of technologies. In that case, those technologies do not include a sensitivity analysis for the hurdle rates so we preferred to keep those values constant in both scenarios and only observed the system's variations for the cases studied by Oxera [47].

Furthermore, we entered two extra scenarios in which the hurdle rate varies over time. These variations were supported by the analysis carried out by Oxera [47], where learning rates of the technologies, the policies and the assimilation of the risks, force a decrease in the implicit risk of the technology so it is acceptable, depending on the technology, a reduction in the mid- or long-term for the current hurdle rates. This can be seen in Table 4 (Note: 'Var' means variable).

(TABLE 4)

### 4.2. TIMES-Norway scenarios

Equivalently to the scenarios described for ETSAP-TIAM, the analysis with TIMES-Norway is based on considering several social discount rates and hurdle rates. For that reason, we considered a set of two different social discount rates: 5% and 15% which correspond with the DR-5 (BaU) and DR-15 scenarios, respectively.

In the case of TIMES-Norway, the reference scenario uses a social discount rate of 5%. Due to time consumption for each run, we decided to restrict the analyses to the previous two cases. This should be enough to observe trends in the behaviour of the energy system in Norway.

Separately, we included the same hurdle rates for the electricity generation technologies as we used in Table 3 and Table 4. As the technology portfolio in TIMES-Norway (see Table 1) is shorter than ETSAP-TIAM portfolio, we considered a pair of scenarios for the following technologies:

(TABLE 5)

New large hydro power (dams) plants have the same hurdle rates in both scenarios. This is due to the stabilization of the technology in terms of maturity: they are commercial and well-proven and no new risks or barriers are expected in the future apart from the ones derived from changes in the load profile (water amounted) in the long-term future. These variations are considered negligible in this study.

## 5. Results and discussion

This section analyses certain common parameters such as electricity production, the levelised costs of the electricity and system costs of the electricity generation technologies. This selection is based on analogous studies and the usual outputs of

TIMES models. However, the assessment is focused on the effects caused on them by both social and technology-specific discount rates choices.

## 5.1. ETSAP-TIAM

### 5.1.1. Electricity production mix

The electricity production technologies have been aggregated in three main categories: fossil, nuclear and renewable. This decision has been made to make analysis easier. Figure 2 presents the electricity production mix for Europe (WEU and EEU regions) using the ETSAP-TIAM model. It includes the seven scenarios of Table 3 for different social discount rates.

(FIGURE 2)

Figure 2 shows the effects of applying a wide range of social discount rates, from 3% to 15%. The slight differences in 2012 are due to the fact that 2012 is not the reference year of the model but the first milestone.

The most interesting result in Figure 2 is the behaviour of the fossil technologies with respect to the entrance of the renewable technologies: the lower the discount rate the higher the renewable contribution. In the reverse way it is possible to say that lower discount rates favour the renewables and punish the fossils whereas high discount rates cause significant shares for fossils in the long term. This happens because the higher the social discount rate, the lower the impact of future extra costs. Social discounting affects all costs in the model, including operational costs.

Separately, the nuclear contribution remains indifferent to the discount rates since no new nuclear plants are installed and the existing capacity decreases gradually towards 2050. This is due to the fixed behaviour of the existing nuclear capacities, limited by their activity licenses. The differences in the total amount of electricity produced are mainly linked to a change in the energy carrier. This effect is significant with high discount rates because the use of fossil technologies increases the use of heat in CHP plants (mainly in industry).

There is another aspect of this result to be considered: the evolution of the electricity mix. It seems clear that the effect of the discount rates is significant from 2030 and, in particular, the case of low discount rates respect to the same scenario in 2012. Under these circumstances, the entrance of the renewable technologies is remarkable (from a quarter to a half). Attending to the behaviour of the technologies within the mix, it has been observed that using high social discount rates favours the presence of fossils via coal IGCC plants. In addition, something occurs in the renewable side of the mix: solar PV technology grows in the long term in detriment of the wind onshore (mostly), biomass and even ocean-related technologies. This modelling interplay takes place as a result of the relative costs that define each technology, with wind and ocean in particular having a higher capital cost and fixed operation cost, but lower variable costs.

As pointed out in Section 2, the usual value in most of the TIMES models for the social discount rate is 5%. Nevertheless, results from Figure 2 show the importance of selection of the discount rate for the energy system. Slight variations in this value involve significant changes in the evolution of the entire system. In consequence, it seems appropriate to discuss the choice of the social discount rate and, going further, if this parameter is enough to cope with the risks presumed for each of the technologies. Figure 3 answers this question considering the scenarios for a pair of technology-specific discount rates applied on electricity generation technologies (see Table 3).

(FIGURE 3)

The electricity production mixes resulting from using different hurdle rates in the electricity production technologies are shown in Figure 3. There, the DR-5 scenario has been used as Business as Usual and the other scenarios, HR-High and HR-Low, include extra hurdle rates beyond the 5% social discount rate.

The main result observed is the higher contribution of the fossil technologies in the long term with respect to the DR-5 scenario. This happens because the introduction of the hurdle rates of Table 3 in the system increases the risks associated to those technologies and therefore, renewables are less favoured than fossils. Going further, if we compare HR-High and HR-Low scenarios their behaviour is almost the same with some peculiarities: HR-High scenario involves high contribution from coal and a low input from solar PV technology, and vice versa in case of HR-Low scenario.

In consequence, we have two different results. First, the effect of considering hurdle rates for the electricity production technologies is a way (implicit) to assume the risks associated with the private investments. This consideration is necessary because the investments in new technologies are carried out by private firms instead of governments. The social discount rate establishes the risk (implicitly) at which the society wishes to pay any new investment now but looking at the future. Considering the results from Figure 2 and the comparison with Figure 3, it seems clear that every TIMES modelling exercise should include technology-specific discount rates to put the extra risks in the correct place. If not, modellers will be analysing unrealistic scenarios. In other words, the difference in the graphs justifies that government policy aims to reduce the risk by a subsidy level equivalent to the time-dependent component of the hurdle rate. Secondly, by comparing the HR-High and HR-Low scenarios we can conclude that the lower the hurdle rates the higher the renewable contribution. This is analogous to the results observed in Figure 2 but at a more detailed level.

Furthermore, results from Figure 3 are in line with those obtained by Simões *et al.* [23] using the JRC-EU-TIMES model for EU28. They evaluated the behaviour of the electricity generation mix up to 2050 by varying the discount rates of specific technologies. The authors discussed the share of different electricity technologies in 2050 pointing out that there is interplay between gas and coal on the one hand, and renewables, in particular wind, on the other. They conclude that with lower discount rates, wind technologies grow considerably. Besides, tidal technologies become competitive in 2050 though their deployment remains low. This is a consequence of the relative costs of these technologies, with wind and ocean in particular having a higher capital cost and fixed operation cost, but lower variable costs.

Additionally, Simões *et al.* [23] observed that the share of renewables in total electricity produced does not change. This result is different than ours. The reason is founded on the assumption they made: authors created the sensitivity analysis using two scenarios, Low (-20%) and High (+20%) technology discount rates, but assuming the same variations for all the technologies. In our work, we used the discussion of Oxera [50] to improve the veracity of the high and low discount rates. Consequently, this work goes further than Simões *et al.* [23] assessment and making it possible to observe the fossils-to-renewables transition.

In addition, we tested the HR-High-Var and HR-Low-Var scenarios described in Table 4 as a sensitivity analysis exercise to observe the consequences of modifying the hurdle rates in the future according to Oxera [47]. Results showed that differences respect to the HR-High and HR-Low scenarios are negligible. Thus, the system is not affected by the evolution of the technology-specific discount rates of the technologies.

Summarising, ETSAP-TIAM results show that the choice of the social discount rate is crucial because it exerts influence on the entire system. Furthermore, the choice of the hurdle rates seems mandatory to enrich the analysis and it should be assumed as a refinement.

### 5.1.2. System costs

Kanan and Turton [28] developed a sensitivity analysis not only for the electricity production mix but also for the system costs. In that case, the authors assessed the role of the nuclear technologies using the Swiss TIMES model. Even though the study was very particular and the assessment of the hurdle rates was made for two cases (6% and 10%) applied on the nuclear technologies, the parameters analysed were the electricity generation mix and the electricity generation cost. Moreover, as Simões *et al.* [23] realised, the relative costs of the technologies included in TIMES are crucial when you are discussing the choices of the model. As costs are considered in the objective function and weighted by the discount factor (see Eq. (4)) and then, they are minimised, it seems relevant to analyse the effect of using different social discount rates and hurdle rates on the system costs.

With regard to the magnitude of the changes caused by variations in the social discount rate, Figure 4 shows that there are variations up to 20% amongst scenarios for each milestone. This gives an idea about the need of selecting carefully the social discount rate in the beginning of the modelling exercise.

Besides, results from the modelling showed that the effect of adding technology-specific discount rates is minor and it has consequences in the final amount of electricity produced with each technology but it is not decisive in terms of technology selection (by TIMES). This can be concluded due to the negligible differences of the total discounted system costs between the reference scenario (DR-5) and the HR-High and HR-Low scenarios.

The following Figure 4 shows the annualised costs of the electricity production system in Europe for all the scenarios of Table 2 considering variations of the social discount rate.

(FIGURE 4)

Figure 4 displays the contribution of the investment costs, fixed costs and variable costs of the electricity production sector in EEU and WEU altogether. Costs are disaggregated by modelling milestones (annualised). As in Simões *et al.* [23], total costs are higher in the long term and there is a trend: the higher the global discount rate, the higher the investment cost contribution. Similar results were obtained by Kannan [27]. However, this conclusion is not valid for DR-13 and DR-15 scenarios. In those cases, the system preference for fossil fuel technologies (see Figure 2) is so significant that preceding trend changes. In addition, one could expect an increase in the variable costs but that does not happen. This is due to the fact that fossil fuels entrance takes place via industrial CHPs which use heat as co-product and then those costs are not included in Figure 4. As costs disaggregation presented in Figure 4 is just for the electricity generation sector, without considering the costs analysis for the electricity as co-product in industry, a diminution in DR-13 and DR-15 scenarios is observed to the extent that industrial CHP plants are deployed in the long term. In further analyses, we checked the total system costs. In such cases the growth of the variable costs linked to the use of fossils is noteworthy, especially in the long term. This happened because in our modelling exercise we did not impose climate policy targets.

Furthermore, by looking at the total system costs it can be concluded that this disaggregation is not very affected by the selection of different social discount rates. In fact, the effects take place but at a different level, as discussed in Figure 4, that is, there is interplay amongst sectors by means of the energy carriers.

Also Simões *et al.* [23] concluded that aggregated indicators of energy demand are not significantly sensitive to variations in hurdle rates. When looking at the direction of the changes, total system costs and annual costs in 2050 increase with higher discount rates, reflecting a higher cost for capital investments.

## 5.2. TIMES-Norway

### 5.2.1. Electricity production mix

TIMES-Norway is a national energy optimisation model that has been used by IFE in several projects and studies. Lind *et al.* [43] analysed the electricity price by sector and region under several policies as well as the fuel use in the transport sector in 2020. In consequence, this paper goes further analysing the effects in TIMES-Norway of varying the social discount rates and the technology-specific discount rates for the electricity generation technologies.

Due to the time consumption for a regular run in TIMES-Norway, the two scenarios for the social discount rates are 5% and 15%. Next, it is shown the electricity generation mix for each case (see Figure 5).

(FIGURE 5)

The behaviour of the hydropower production is the first relevant result in Figure 5. Due to the stability of this technology and its assumed lifetime (50 years), it produces electricity constantly until the end of horizon. This happens both for the existing run-of-river (RoR) and for the hydropower produced in dams. As they are existing capacities, the effect of the discount rate cannot be observed. Additionally, the installation of new hydro plants does not seem to be affected by variations in the social discount rate. In contrast, we can observe the differences in the appearance of wind technologies. Particularly, from 2030 the analysis with low discount rates favours wind power. Besides, offshore wind becomes significant with low discount rates from 2040 reaching more than 5% of electricity production by 2050. The scenario with high discount rates disincentives the appearance of new wind and, as we will see, causes a decrease in the net exporting balance of Norway.

(FIGURE 6)

Figure 6 shows the imports and exports of electricity between Norway and its neighboring countries considering low and high discount rates. As discussed previously, the lower the discount rates in TIMES-Norway the higher the wind contribution and consequently the higher the net exporting balance of Norway. In summary, reducing the social discount rate, that is, reducing the risk assumed by the society for making new investments implies an overcapacity of wind (and thus increases the electricity export from Norway). In contrast, this situation could be controversial because this scenario would involve a strong dependency to the market situation.

For that reason, it seems mandatory to introduce technology-specific discount rates for the electricity production technologies in TIMES-Norway. When we consider the rates of Table 6, the electricity mixes have the following form.

(FIGURE 7)

The introduction of the hurdle rates for the specific technologies is a way to take into account the risks and barriers of each technology. Figure 7 shows the effect of increasing the discount rates. In the HR-Low scenario, the decrease of the wind begins to be significant from 2040. In the HR-High scenario, the reduction in wind power starts from 2030. Besides, in both cases the wind offshore technologies do not emerge.

The hurdle rates considered for the wind onshore in this analysis were 7% for the HR-Low scenario and 10% for the HR-High scenario (see Table 6). This means an additional increase in the assumed private risk from 2% to 5%. In the case of the new hydropower, the HR- scenarios do not increase the social 5% significantly (new dams assume 7% as hurdle rate in both cases because the technology is very mature).

Likewise as before, the competition between hydro and wind causes a move in the import/export of electricity.

(FIGURE 8)

Figure 8 expresses the imports and exports of electricity when hurdle rates are considered. The introduction of extra risk via the hurdle rates reduces the exports and increases the imports in the long term.

Having an adequate social discount rate and considering the hurdle rates of the technologies for producing electricity, this would lead to a result in between the HR-scenarios of Figure 7 for the electricity technology mix and a net exporting balance in 2050 going from 26 TWh for low hurdle rates to 22 TWh for high hurdle rates.

### 5.2.2. System costs

As in Section 5.1.2, the analysis of the system costs in the TIMES-Norway model allows detecting the relevant impact of varying the social discount rates.

(FIGURE 9)

Looking at the results from Figure 9, we observe that high social discount rates cause an increase in the annualised system costs in the long term. This corresponds to the result presented in Figure 4. The main difference is linked to the investment costs, much higher in the case with DR-15 than DR-5 (+38% in 2050). Besides, the increase of the variable costs is also significant with high discount rates, 13% in 2050. This strengthens the idea of prioritising the discussion on declaring the investment costs of a technology and, to an extent, to discuss also the variable costs in depth.

To observe the specific changes of applying different technology-specific discount rates to the electricity generation processes, see Figure 10.

(FIGURE 10)

Figure 10 shows the disaggregated costs components of the Norwegian energy system under different cases. The introduction of extra risks via hurdle rates (Table 6) implies negligible changes in the costs. In particular, the total discounted system costs for the whole horizon are only 0.3% higher in HR-Low than DR-5 and 0.9% higher in the case of HR-High with respect to DR-5. Regarding the variations of the hurdle rates, it is observed a significant change in the variable costs of the system when we increase the percentages. In the HR-Low scenario, the variable costs grow up to 6% in 2050 with respect to DR-5 and, for the HR-High scenario, variable costs grow even more, almost 8% by 2050 with respect to the DR-5 value. Consequently, variations in the hurdle rates of the electricity production technologies involve interplay between the investment and variable costs of the entire energy system, mainly based on the selection of renewable versus fossil technologies.

In summary, high hurdle rates imply higher variable costs, that is, the model prefers to use traditional (mature) solutions instead of (new) renewables. We can see that in Figure 3 for ETSAP-TIAM model considering that “traditional” here has to be understood as fossil. This conclusion gives an idea about how to face the economic assumptions in a TIMES modelling exercise.

Then, it seems appropriate to prioritize: firstly, the introduction of the investment costs of the technologies portfolio in TIMES (due to the order of magnitude they will be very affected by the social discount rate); secondly, the introduction of the variable costs of the technologies (since they will be relevant if hurdle rates are considered for the introduction of extra risks associated to each technology); and finally, the selection of both the social discount rate and the hurdle rates of the technologies.

## 5.3. Discussion on discount rates

### 5.3.1. Qualitative remarks

In the preceding sections we have observed the effects of modifying the social discount rate of the entire energy system and the hurdle rates of specific technologies. It is known that TIMES models are not very detailed in the way they consider risks and barriers related to the new technologies and their potential deployment.

Regarding the issue of selecting an appropriate social discount rate, the Norwegian Ministry of Finance recommends using a percentage of 4% for Norway [46]. The ministry discusses in depth the choice of this value founding its decision in both the use of CAPM results and the recommendations of a committee of experts. But when the ministry decides to assume a value for the social discount rate they are not only considering the risk undertaken by the society. The risk is disaggregated into two components: systematic and unsystematic. The systematic component means the risk priced in the market that cannot be diversified away by holding different securities. On the other hand, the unsystematic risk is the one that depends on project specific circumstances. Consequently, it is required to discuss what to consider in the assumption of risks within the choice of a figure for the discount rate.

Schleich [50] summarised the barriers to energy efficiency measures (as an example) based on Sorrell *et al.* [18]: financial risk, understood as market uncertainty; imperfect information, in the sense of cost effective opportunities missed; hidden costs, such as overhead costs, failures in the budgets, extra costs, etc.; access to capital; split incentives, means that all actors should perceive the benefits of the investment; and bounded rationality. Other authors have carried out particular assessments of the discount rates in bottom-up models [14] and even developed a brief sensitivity analysis of the discount rates using JRC-EU-TIMES [23]. For that reason, our work is relevant helping to reinforce the modelling assumptions undertaken by the TIMES modellers worldwide.

The assessment of the effects of modifying the lifetime of the technologies instead of using hurdle rates has not been carried out in this work.

### 5.3.2. Regional approach on discount rates

The use of ETSAP-TIAM and TIMES-Norway has shown the consequences of selecting different discount rates (social and technology-specific) in different energy systems.

In the ETSAP-TIAM case, analysis was based on Europe and the consequence of using low social discount rates was a large contribution of renewables in the long term and, vice versa, high discount rates favoured the entrance of fossils via coal IGCC and natural gas. This result is in line with Mallah and Bansal [26], who observed that at lower discount rates, coal was the least preferred technology. On the contrary, results from TIMES-Norway showed a competition between renewable options such as hydro and wind in the Norwegian electricity mix. In addition, the consideration of the electricity import/export trade was very pertinent in that case.

Besides, the regional approach in the analysis of costs is very linked to the discussion on electricity production mixes. ETSAP-TIAM results show the relevance of the investment costs (capital intensive) for the European energy system with respect to the variable and fixed costs (see Figure 5). This happens because future mixes are highly renewable in all the cases. In contrast, TIMES-Norway results showed the importance of the variable costs in an energy system whose electricity mixes are almost 100% renewable since the reference year.

Some recent studies have proven the importance of focusing on the discount rates debate referred to energy planning. For instance, de Jong et al. [51] discussed the convenience of using 5% discount rate in first approach and 10% resulted as an optimal value when externalities were considered. In 2013, Pereira Jr. et al. [52] published an article for the electricity sector planning in Brazil discussing the suitability of using lower discount rates. Those authors proposed 8% for the specific case of Brazil. Larsson et al. [53] remarked that the selection of the discount rate is one of the most important cost factors for capital-intensive power generating technologies. They observed that discount rate assumptions diverge significantly among literature, making the costs figures difficult to compare.

In regions where studies tend to diverge other assumptions are considered such as the financial life time, decommissioning and renewal overheads, assumptions on residual values, and management costs. Regional conditions explain some of the differences in the cost obtained, meaning that it will be difficult to compare and/or use costs from very dissimilar regions. Consequently, we can conclude that regionalisation is extremely important since each electricity mix has its particular characteristics and they must be considered properly.

From literature, Hansson et al. [54] have published recently an article on the controversy about who decides and on what grounds with regards to the social discounting. After interviewing Swedish policymakers about this issue –discount rates and time horizons in particular– authors concluded that at present the choice of discount rates in national environmental policy is “uncoordinated, insufficiently justified, insufficiently transparent, and therefore not politically accountable” (ibid, p. 11) so they propose a coordinated plan at national level to evaluate this concern.

## 6. Conclusions

TIMES uses the discount rates (both social and technology-specific) as the only way to take into account the risk and barriers of the available technologies to be installed. Consequently, this fact places all the significance in the choice of the discount rate. In TIMES, this parameter is entered exogenously so it seems mandatory to justify clearly why we selected this or that figure.

In particular, we have observed the significant changes of using different discount rates in the electricity production mix and system costs. This fact strengthens the need of rigorousness therefore we recommend that some discussion and sound references should be added prior to assume a percentage.

As expected, in the ETSAP-TIAM model for Europe low social discount rates entailed great contributions of renewable technologies and reversely, high social discount rates favoured the use of fossils. In the case of TIMES-Norway, due to the high degree of renewables in the current energy system, the competition happens between hydro and wind power. Low social discount rates favoured the wind and a high net exporting balance. Additionally, the assessment of the hurdle rates (applied on the electricity production technologies) showed that the electricity mix remained almost unaffected in ETSAP-TIAM but relevant changes took place in TIMES-Norway. In this case, the implicit consideration of risks via hurdle rates punishes the new technologies so the appearance of wind solutions goes down with respect to the case without hurdle rates. Thus, the higher the hurdle rate is the lower the wind power contribution. Overall results can be observed in Table 6.

(TABLE 6)

Modelling results showed that the choice of the social discount rate is crucial because exerts influence on the entire system whereas the choice of the hurdle rates seems necessary to enrich the analysis (bringing representativeness to the results) and it should be assumed as a fine-tuning assessment.

This work presented a detailed assessment of the importance of the discount rates, both social and technology-specific, used in several energy systems models at national and European level and, as result, some concerns and recommendations were found. Consequently, the objective of this paper was met completely.

Finally, we recommend using a reference value not higher than 4-5% for the social discounting in European countries since it is necessary to assume an inner inevitable risk due to barriers to the entrance of new technologies as well as some extra unpredictable risks such as natural disasters, political changes and/or projects difficulties. Also it seems mandatory to include technology-specific discount rates for each of the technologies considered in the TIMES portfolio, especially in highly renewable energy systems, in order to take into account the particular risks assumed by each technology.

## Abbreviations

BFG, Blast Furnace Gas. CAPM, Capital Assets Pricing Model. CCS, Carbon Capture and Storage. CHP, Concentrated Heat and Power. COG, Coke Oven Gas. DR, Discount Rate. GDP, Gross Domestic Product. HFO, Heavy Fuel Oil. HR, Hurdle Rate. IGCC, Integrated Gasification Combined Cycle. IRR, Internal Rate of Return. LNG, Liquified Natural Gas. LPG, Liquified Petroleum Gas. LWR, Light Water Reactor. MARKAL, MARKet Allocation model. MARR, Minimum Acceptable Rate of Return. MSW, Municipal Solid Waste. NGCC, Natural Gas Combined Cycle. NOK, Norwegian Kroner. NPV, Net Present Value. PBMR, Pebble Bed Modular Reactor. PV, Photovoltaic. RoR, Run-of-River. TIAM, TIMES Integrated Assessment Model. TIMES, The Integrated MARKAL-EFOM System.

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## Figure captions

**Figure 1.** Schematic structure of the TIMES-Norway model [43]

**Figure 2.** Electricity generation mix in Europe considering different social discount rates

**Figure 3.** Electricity generation mix in Europe considering different hurdle rates for the electricity generation technologies

**Figure 4.** Annualised costs of the electricity production sector in Europe for several social discount rates

**Figure 5.** Electricity generation mix in Norway for 5 % and 15 % discount rate

**Figure 6.** Electricity trade of Norway with several social discount rates

**Figure 7.** Electricity generation mix in Norway using hurdle rates for the electricity generation technologies

**Figure 8.** Electricity trade for Norway considering hurdle rates for the electricity production technologies

**Figure 9.** Annualised system costs for Norway using two different social discount rates

**Figure 10.** Annualised system costs for Norway using hurdle rates in the electricity generation technologies

## Table captions

**Table 1**. Potential electricity production by technology included within the TIMES-Norway model [43]. Note: (1) Onshore wind is disaggregated at project level in TIMES-Norway

**Table 2.** Scenarios description considering different social discount rates in ETSAP-TIAM model [23:38]

**Table 3.** Hurdle rates of electricity production technologies included in ETSAP-TIAM. Notes: (1) Extracted from Oxera [47]. (2) Extracted from Simões *et al*. [23]. (3) Extracted from ETSAP-TIAM templates. (4) Extracted from Morris-Marsham [48]. (5) Extracted from IRENA [49]

**Table 4.** Scenarios description concerning sensitivity to hurdle rates variations in ETSAP-TIAM. Note: “Var” refers to “variable”

**Table 5.** Hurdle rates for the electricity production technologies considered in TIMES-Norway

**Table 6.** Comparison of overall results with different discounting options

**Table 1.** Potential electricity production by technology included within the TIMES-Norway model [43]. Note: (1) Onshore wind is disaggregated at project level in TIMES-Norway

| **Electricity production technologies** | **2010 (TWh/yr)** | **2020 (TWh/yr)** |
|---|---|---|
| Existing hydropower – Dam I | 101.2 | 101.2 |
| Existing hydropower – Run-of-River I | 28.7 | 28.7 |
| Existing hydropower – Capacity expansion | 0 | 6.9 |
| New hydropower – Dam II | 0 | 0 |
| New hydropower – Run-of-River (II & III) | 0 | 26.9 |
| Onshore wind power (1) | 1.1 | 41 |
| Offshore wind power | 0 | 27 |
| Existing gas power plant – NGCC without CCS | 2.0 | 0 |
| New gas power plant – NGCC with CCS | 0 | Unlimited |
| CHP plant – MSW, Biomass, Natural gas | 0 | Unlimited |
| Waste heat recovery in industry | 0.14 | 0.14 |

**Table 2.** Scenarios description considering different social discount rates in ETSAP-TIAM model [23:38]

| Scenario name: | DR-3 | DR-5 (BaU) | DR-7 | DR-9 | DR-11 | DR-13 | DR-15 |
|---|---|---|---|---|---|---|---|
| Social discount rate | 3% | 5% | 7% | 9% | 11% | 13% | 15% |

**Table 3.** Hurdle rates of electricity production technologies included in ETSAP-TIAM. Notes: (1) Extracted from Oxera [47]. (2) Extracted from Simões *et al*. [23]. (3) Extracted from ETSAP-TIAM templates. (4) Extracted from Morris-Marsham [48]. (5) Extracted from IRENA [49]

| **Technology** | **Scenarios** | |
|---|---|---|
| | **HR-High** | **HR-Low** |
| Biogas (1) | 10% | 7% |
| Biomass (1) | 13% | 9% |
| Natural gas steam turbine (1) | 9% | 6% |
| Natural gas combined cycle (1) | 6% | 6% |
| Hydro Run-of-River (1) | 9% | 6% |
| Nuclear fission (1) | 13% | 9% |
| Solar photovoltaic (1) | 9% | 6% |
| Ocean tidal (1) | 17% | 12% |
| Ocean waves (1) | 14% | 13% |
| Wind offshore (1) | 14% | 10% |
| Wind onshore (1) | 10% | 7% |
| Coal technologies (2) | 5% | 5% |
| Oil technologies (2) | 5% | 5% |
| Natural gas fuel cells (3) | 15% | 15% |
| Geothermal (3) | 10% | 10% |
| Solar thermal (4) | 8.3% | 8.3% |
| Hydro dam (5) | 7% | 7% |

**Table 4.** Scenarios description concerning sensitivity to hurdle rates variations in ETSAP-TIAM. Note: “Var” refers to “variable”

| Technology | Scenarios | | | | | |
|---|---|---|---|---|---|---|
| | HR-High-Var | | | HR-Low-Var | | |
| | 2010 | 2020 | 2040 | 2010 | 2020 | 2040 |
| Biogas | 10% | 10% | 9% | 7% | 7% | 6% |
| Biomass | 13% | 11% | 8% | 9% | 8% | 6% |
| Natural gas steam turbine | 9% | 9% | 8% | 6% | 6% | 5% |
| Natural gas combined cycle | 6% | 6% | 6% | 6% | 6% | 6% |
| Hydro Run-of-River | 9% | 9% | 8% | 6% | 6% | 5% |
| Nuclear fission advanced | 13% | 11% | 9% | 9% | 8% | 6% |
| Solar photovoltaic | 9% | 9% | 8% | 6% | 6% | 5% |
| Ocean tidal | 17% | 17% | 16% | 12% | 12% | 11% |
| Ocean waves | 14% | 14% | 13% | 13% | 10% | 9% |
| Wind offshore | 14% | 14% | 13% | 10% | 10% | 9% |
| Wind onshore | 10% | 8% | 8% | 7% | 6% | 5% |
| Coal technologies | 5% | 5% | 5% | 5% | 5% | 5% |
| Oil technologies | 5% | 5% | 5% | 5% | 5% | 5% |
| Natural gas fuel cells | 15% | 15% | 15% | 15% | 15% | 15% |
| Geothermal | 10% | 10% | 10% | 10% | 10% | 10% |
| Solar thermal | 8.3% | 8.3% | 8.3% | 8.3% | 8.3% | 8.3% |
| Hydro dam | 7% | 7% | 7% | 7% | 7% | 7% |

**Table 5.** Hurdle rates for the electricity production technologies considered in TIMES-Norway

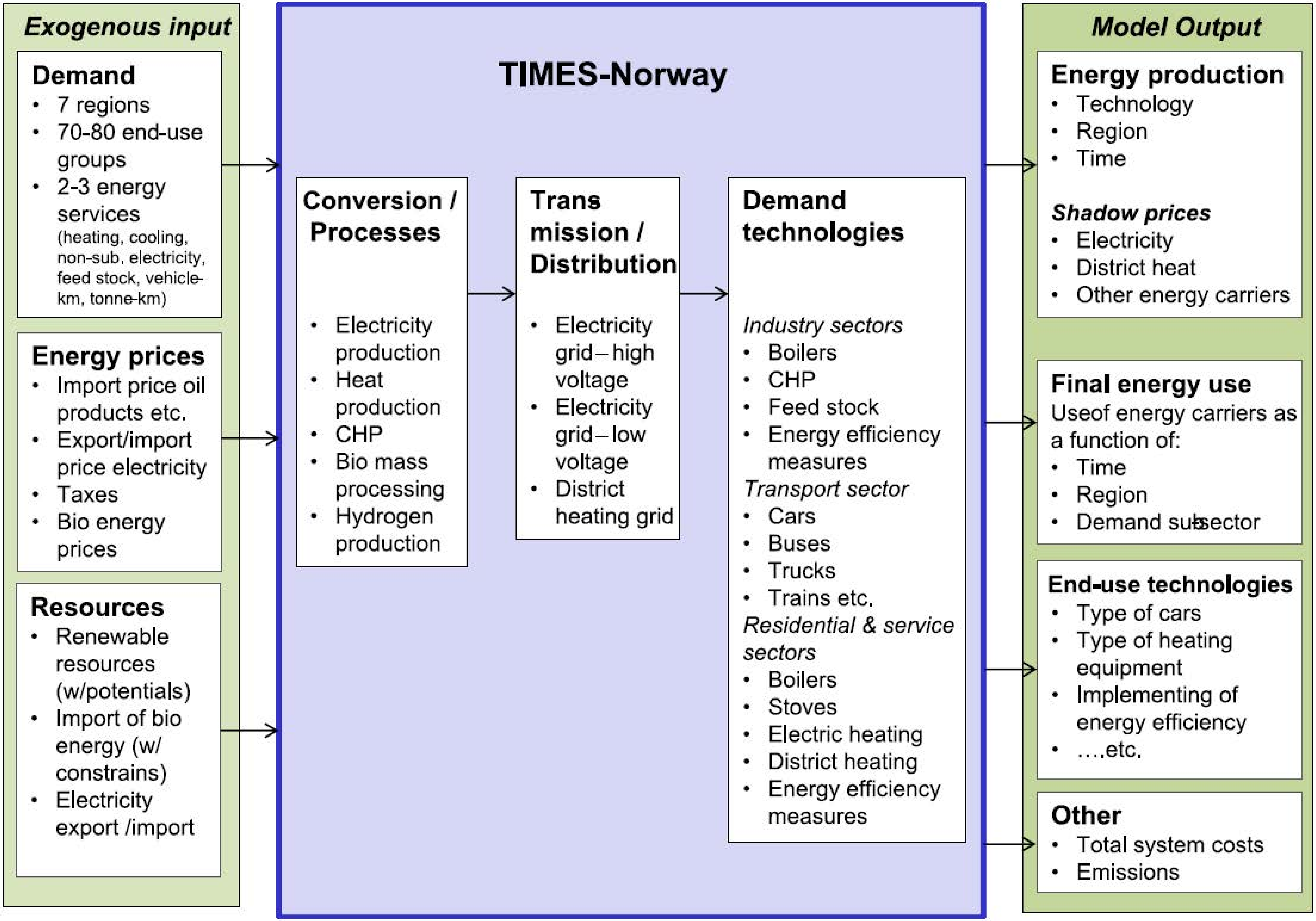
| **Technology** | **Scenario** | |
|---|---|---|
| | **HR-High** | **HR-Low** |
| New hydropower – Dam | 7% | 7% |
| New hydropower – Run-of-River | 9% | 6% |
| Onshore wind power | 10% | 7% |
| Offshore wind power – Shallow | 14% | 10% |
| Offshore wind power – Deep sea | 15% | 11% |
| New gas power plant – NGCC with CCS | 17% | 12% |
| CHP plant – MSW, Biomass, Natural gas | 13% | 9% |
| Waste heat recovery in industry | 13% | 9% |

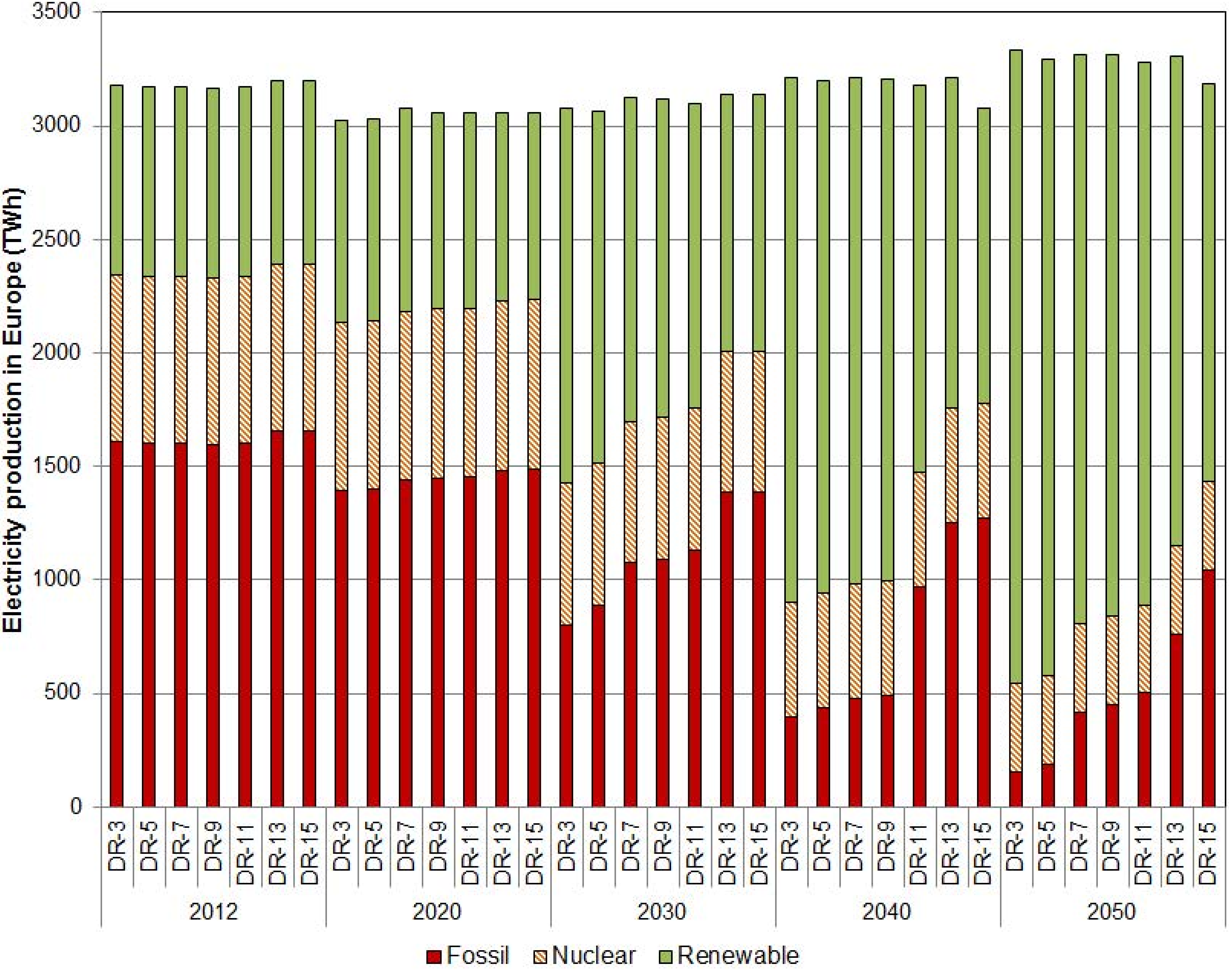
**Table 6.** Comparison of overall results with different discounting options

| ETSAP - TIAM | | | | |
|---|---|---|---|---|
| | **Discounting** | **Value** | **Short term (2020)** | **Long term (2050)** |
| **Electricity Production** | Social | Low | *Renewables 46%, nuclear 25%, fossils 29%* | *Renewables 84%, nuclear 11%, fossils 5%* |
| | | High | *Renewables 48%, nuclear 25%, fossils 27%* | *Renewables 27%, nuclear 12%, fossils 55%* |
| | Technology specific | Low | *It considers a low social discount rate (5%). The effects are very low: renewables 48%, nuclear 25%, fossils 27%* | *It considers a low social discount rate (5%). The effects are significant: renewables 65%, nuclear 12%, fossils 23%* |
| | | High | *It considers a low social discount rate (5%). The effects are very low: renewables 49%, nuclear 25%, fossils 26%* | *It considers a low social discount rate (5%). The effects are significant: renewables 58%, nuclear 12%, fossils 30%* |
| **Annual Costs** | Social | Low | *Investment costs involve 82%, fixed costs 13%, variable costs 5%* | *Investment costs 75%, fixed costs 22%, variable costs 3%* |
| | | High | *Investment costs 84%, fixed costs 12% and variable costs 4%* | *Investment costs 84%, fixed costs 13% and variable costs 5%* |
| | Technology specific | Low | *Negligible in terms of system costs* | *Very low in terms of total system costs* |
| | | High | *Negligible in terms of system costs* | *Very low in terms of total system costs* |

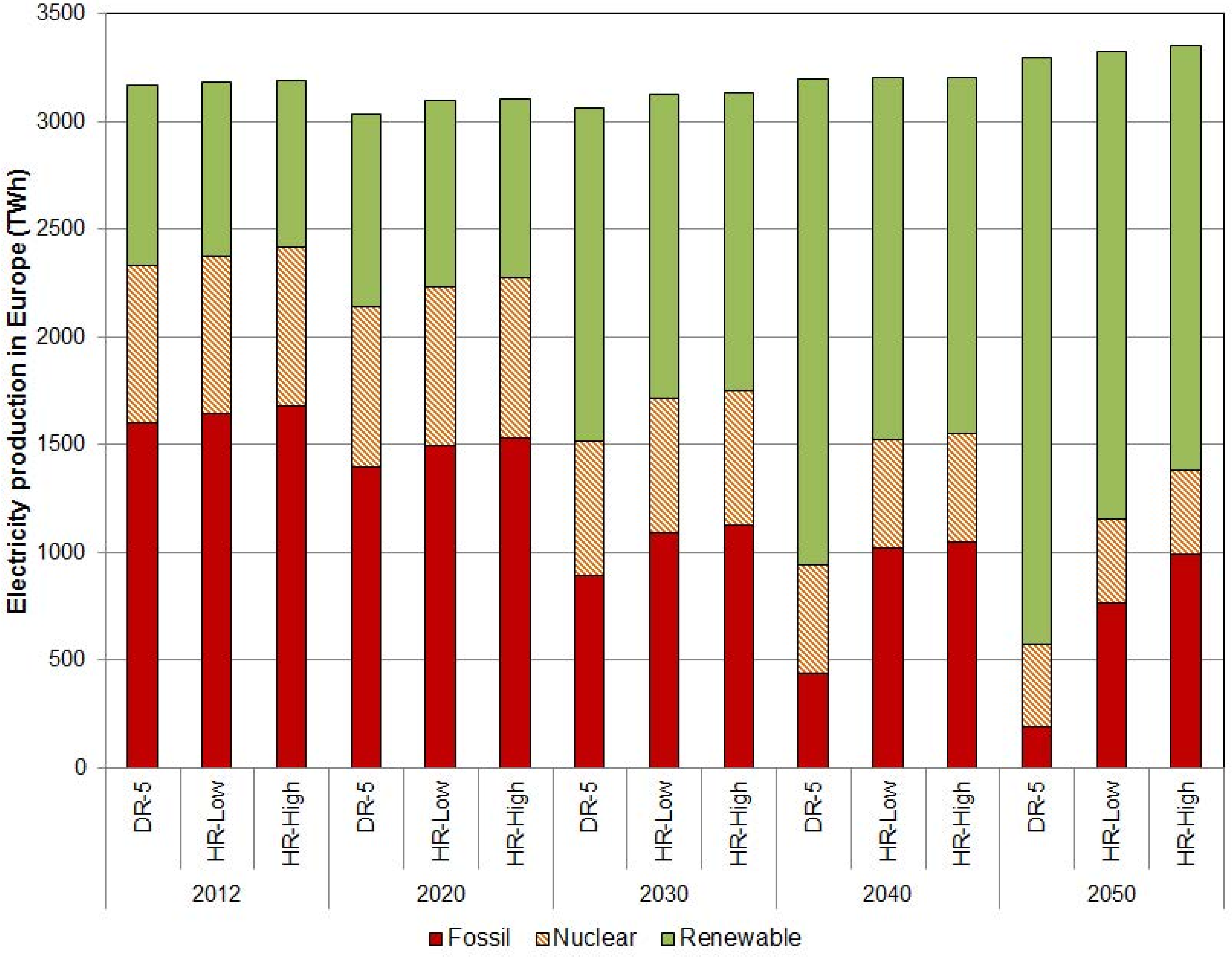
| TIMES-Norway | | | | |
|---|---|---|---|---|
| | **Discounting** | **Value** | **Short term (2020)** | **Long term (2050)** |
| **Electricity Production** | Social | Low | *Wind onshore contribution reaches up to 5%, the rest as in reference year (95% hydro). No contributions from fossils* | *Wind onshore reaches 8% and wind offshore 5%. Rest is hydro. Increase in wind technologies involves reduction in hydro dams (from 70% in 2020 to 55%).* |
| | | High | *Wind onshore contribution reaches up to 2%; rest as in reference year (98% hydro). No contributions from fossils* | *Wind disappears. Its role is assumed by new hydro run-of-river plants up to 15%. Existing dams decrease their contribution (from 70% in 2020 to 62%)* |
| | Technology specific | Low | *No differences between low and high HR. The behaviour is: wind onshore 5%, rest hydro* | *The use of HR punishes wind offshore technologies, which do not appear. Wind onshore involves 4%* |
| | | High | *No differences between low and high HR. The behaviour is: wind onshore 5%, rest hydro* | *The use of HR punishes wind offshore technologies, which do not appear. Wind onshore involves 1%* |

| | | | | |
|---|---|---|---|---|
| **Annual Costs** | Social | Low | *Investment costs involve 30%, fixed costs 55%, variable costs 15%* | *Investment costs involve 42%, fixed costs 40%, variable costs 18%* |
| | | High | *Investment costs involve 39%, fixed costs 48%, variable costs 13%* | *Investment costs involve 47%, fixed costs 38%, variable costs 15%* |
| | Technology specific | Low | *No differences between low and high HR. The behaviour is: investment costs 30%, fixed costs 55%, variable costs 15%* | *No differences between low and high HR. The behaviour is: investment costs 39%, fixed costs 43%, variable costs 18%* |
| | | High | *No differences between low and high HR. The behaviour is: investment costs 30%, fixed costs 55%, variable costs 15%* | *No differences between low and high HR. The behaviour is: investment costs 39%, fixed costs 43%, variable costs 18%* |

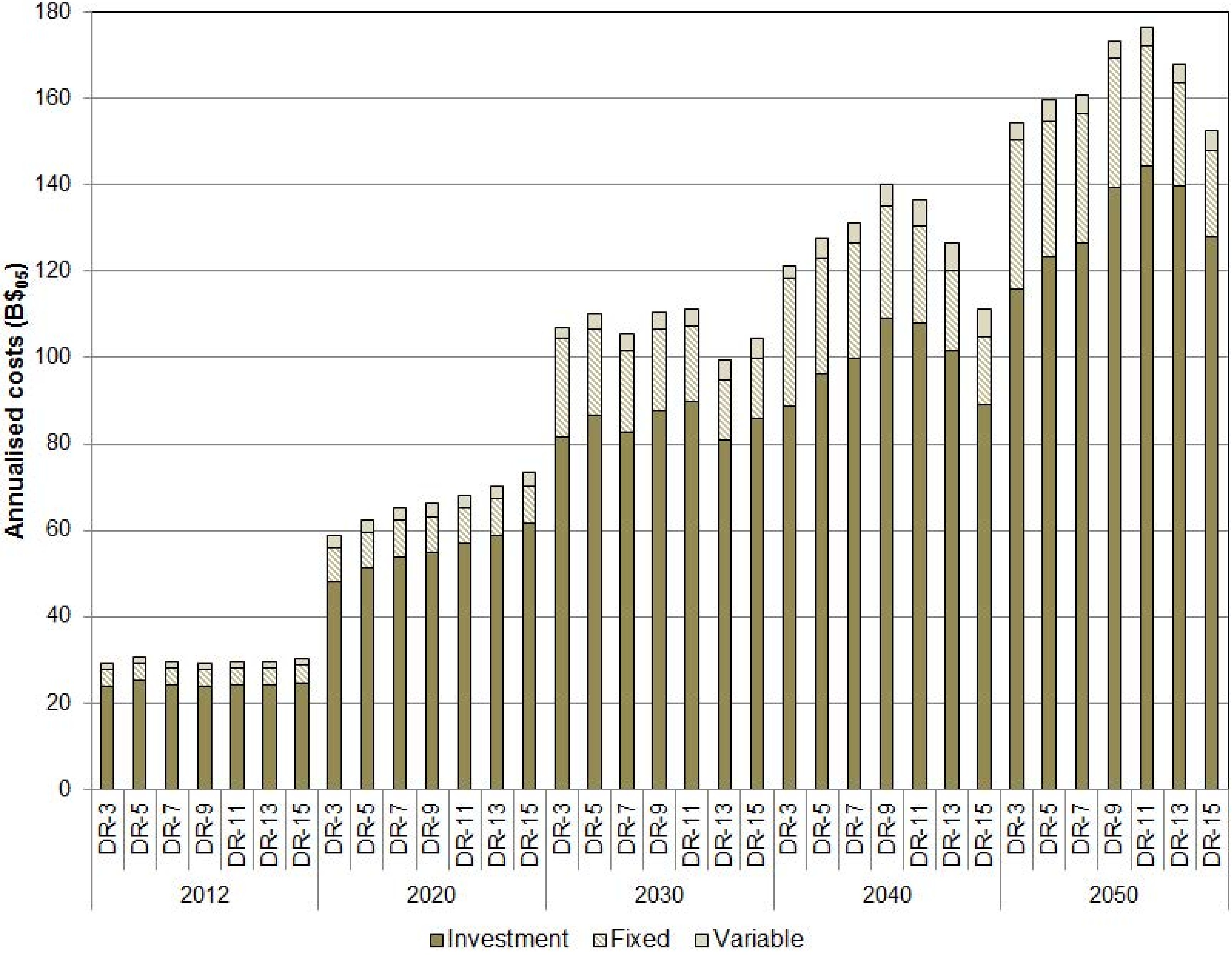

Exogenous input
Demand
• 7 regions
• 70-80 end-use groups
• 2-3 energy services (heating, cooling, non-sub, electricity, feed stock, vehicle-km, tonne-km)
Energy prices
• Import price oil products etc.
• Export/import price electricity
• Taxes
• Bio energy prices
Resources
• Renewable resources (w/potentials)
• Import of bio energy (w/ constrains)
• Electricity export /import
TIMES-Norway
Conversion / Processes
• Electricity production
• Heat production
• CHP
• Bio mass processing
• Hydrogen production
Trans mission / Distribution
• Electricity grid – high voltage
• Electricity grid – low voltage
• District heating grid
Demand technologies
Industry sectors
• Boilers
• CHP
• Feed stock
• Energy efficiency measures
Transport sector
• Cars
• Buses
• Trucks
• Trains etc.
Residential & service sectors
• Boilers
• Stoves
• Electric heating
• District heating
• Energy efficiency measures
Model Output
Energy production
• Technology
• Region
• Time
Shadow prices
• Electricity
• District heat
• Other energy carriers
Final energy use
Useof energy carriers as a function of:
• Time
• Region
• Demand subsector
End-use technologies
• Type of cars
• Type of heating equipment
• Implementing of energy efficiency
• ….etc.
Other
• Total system costs
• Emissions

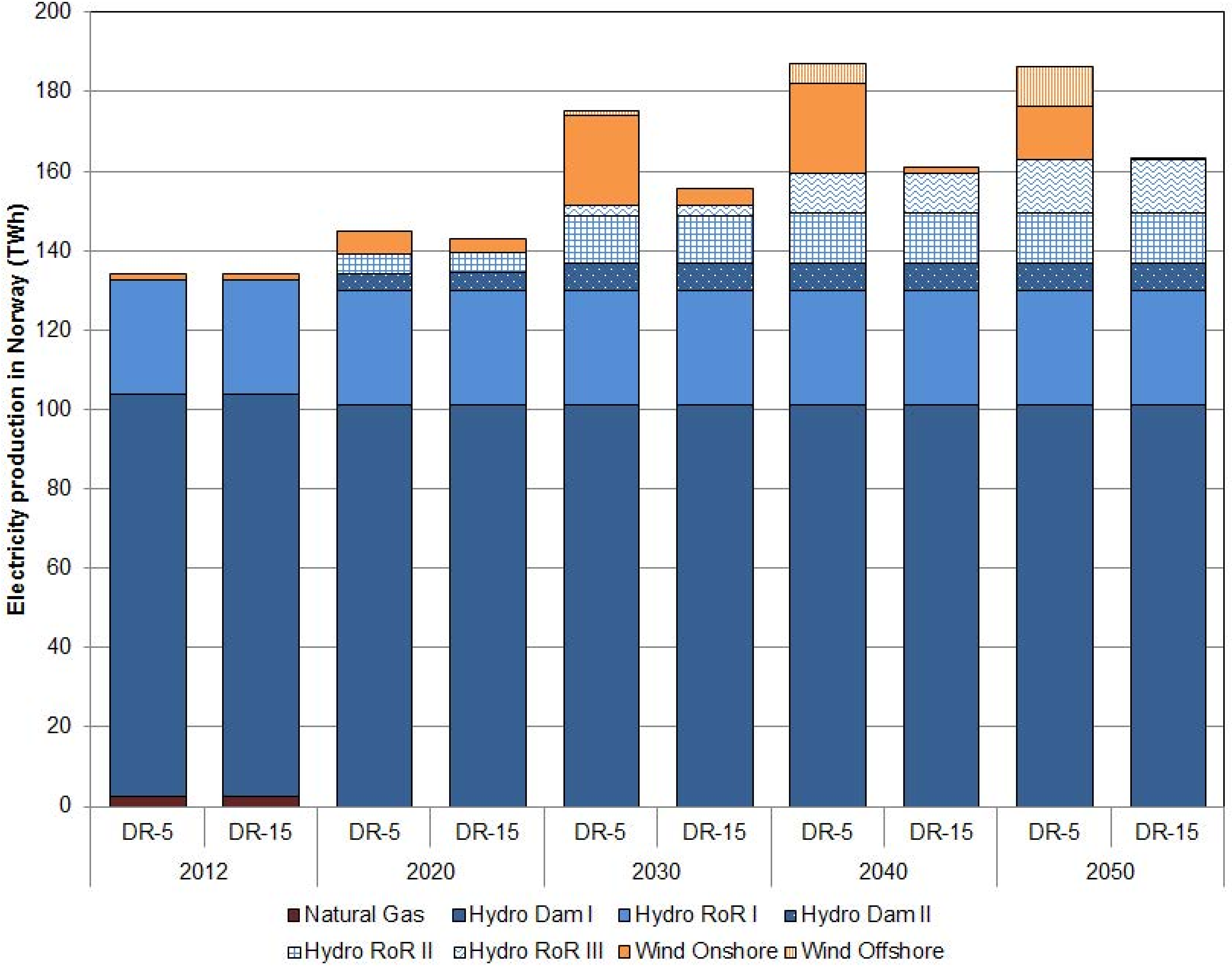


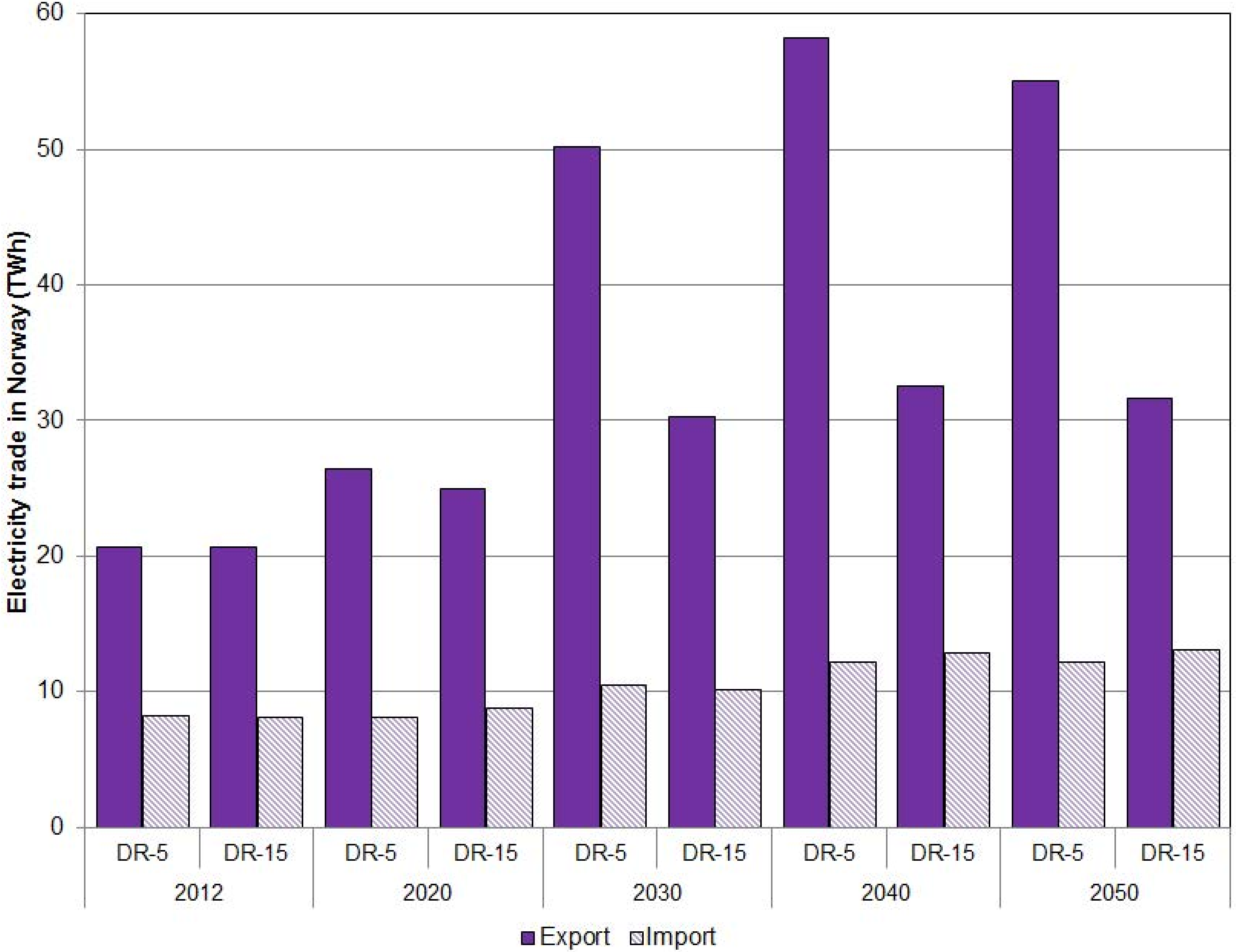
Electricity production in Europe (TWh)
3500
3000
2500
2000
1500
1000
500
0
DR-3
DR-5
DR-7
DR-9
DR-11
DR-13
DR-15
2012
2020
2030
2040
2050
Fossil
Nuclear
Renewable



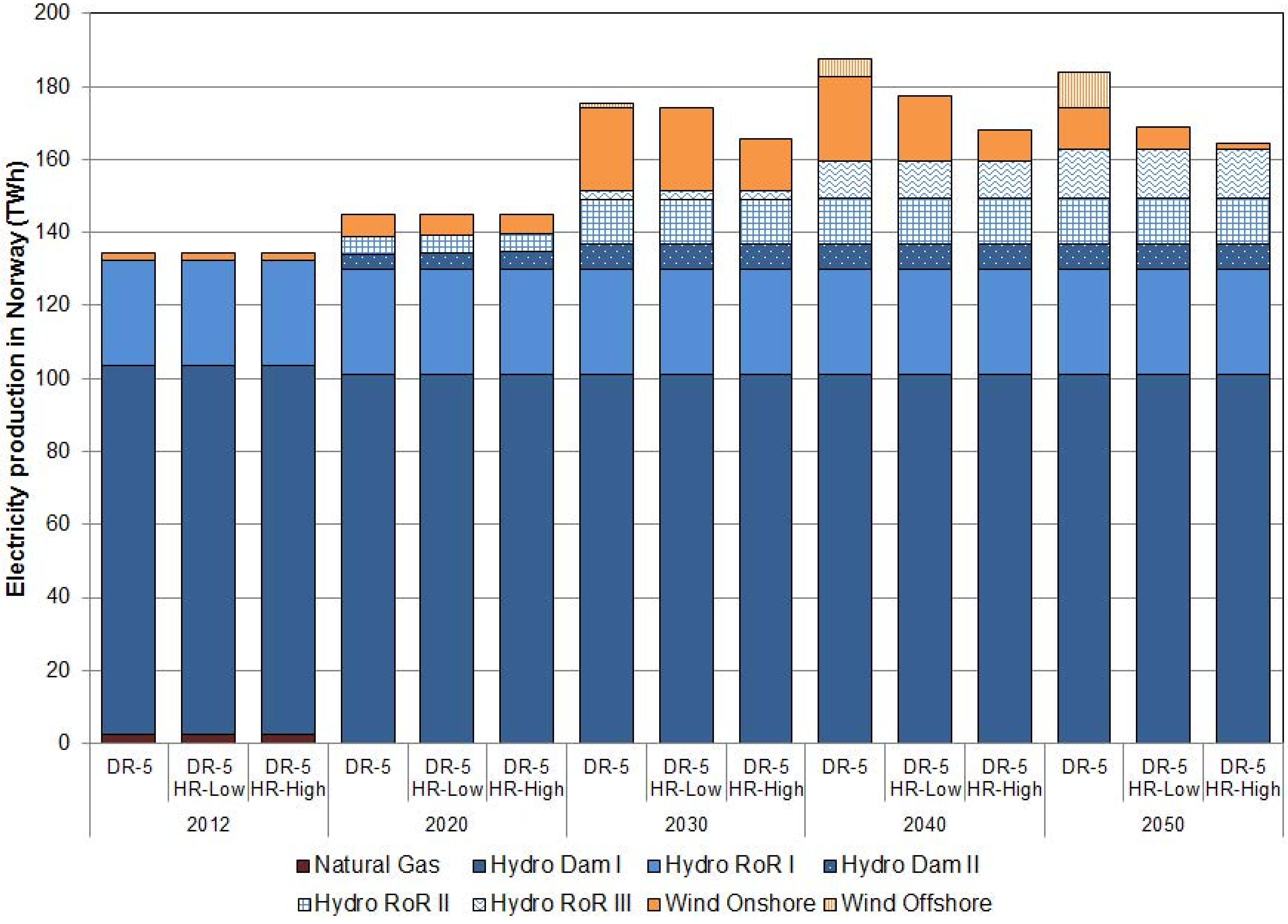
3500
3000
2500
2000
1500
1000
500
0
Electricity production in Europe (TWh)
DR-5
HR-Low
HR-High
DR-5
HR-Low
HR-High
DR-5
HR-Low
HR-High
DR-5
HR-Low
HR-High
DR-5
HR-Low
HR-High
2012
2020
2030
2040
2050
Fossil
Nuclear
Renewable

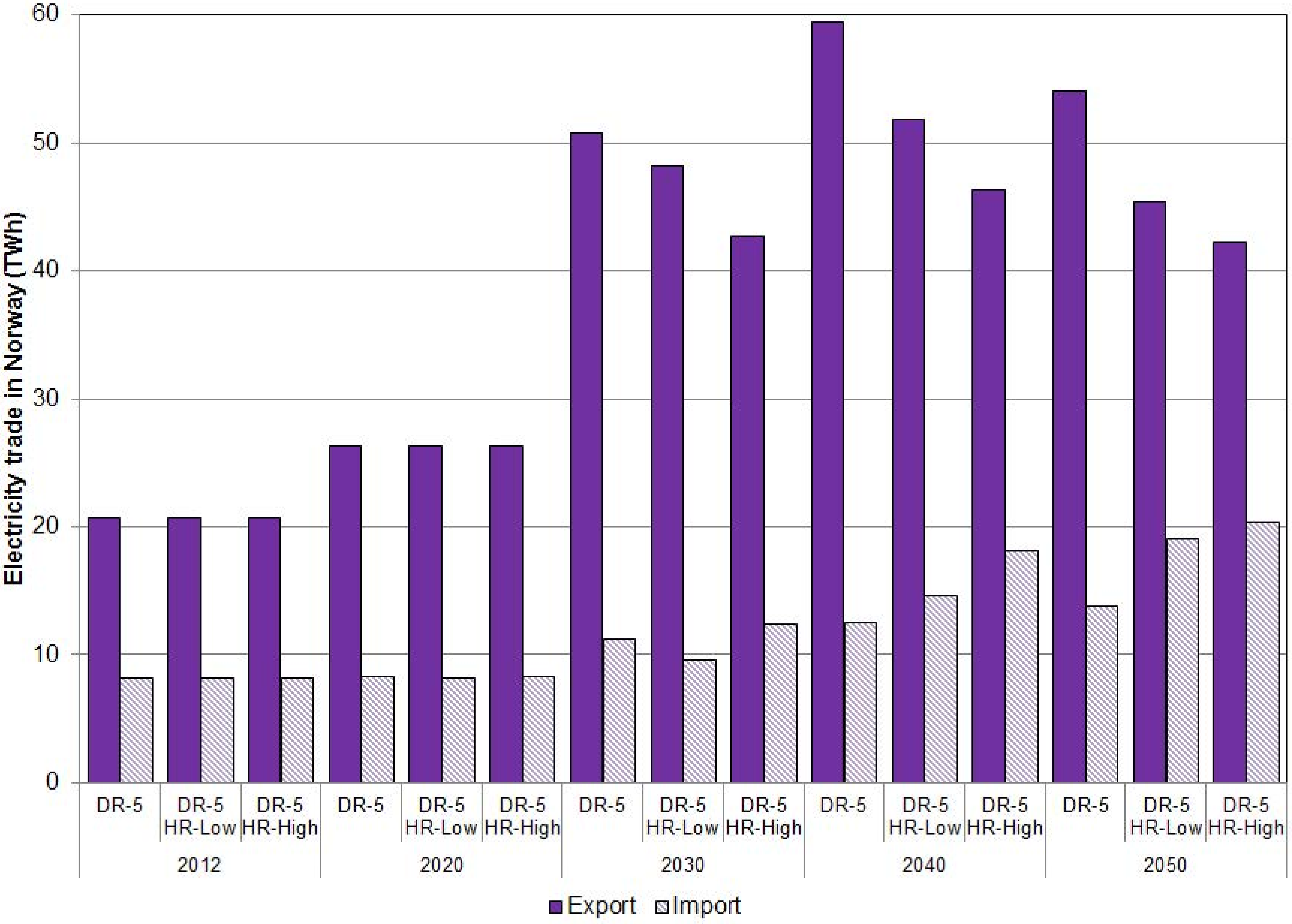

Annualised costs (B$05)
0
20
40
60
80
100
120
140
160
180
DR-3
DR-5
DR-7
DR-9
DR-11
DR-13
DR-15
2012
2020
2030
2040
2050
Investment
Fixed
Variable

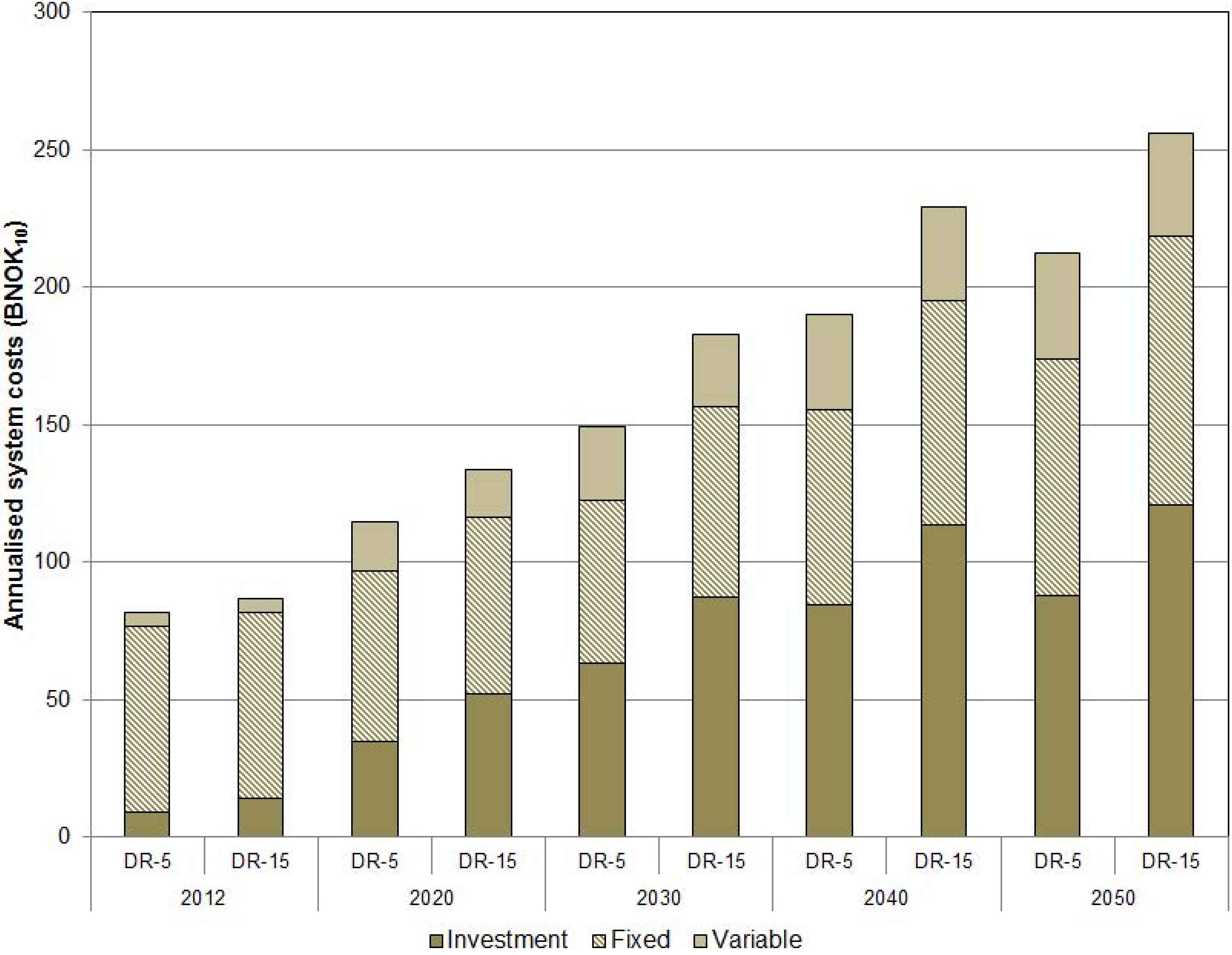

Electricity production in Norway (TWh)
0
20
40
60
80
100
120
140
160
180
200
DR-5
DR-15
DR-5
DR-15
DR-5
DR-15
DR-5
DR-15
DR-5
DR-15
2012
2020
2030
2040
2050
Natural Gas
Hydro Dam I
Hydro RoR I
Hydro Dam II
Hydro RoR II
Hydro RoR III
Wind Onshore
Wind Offshore

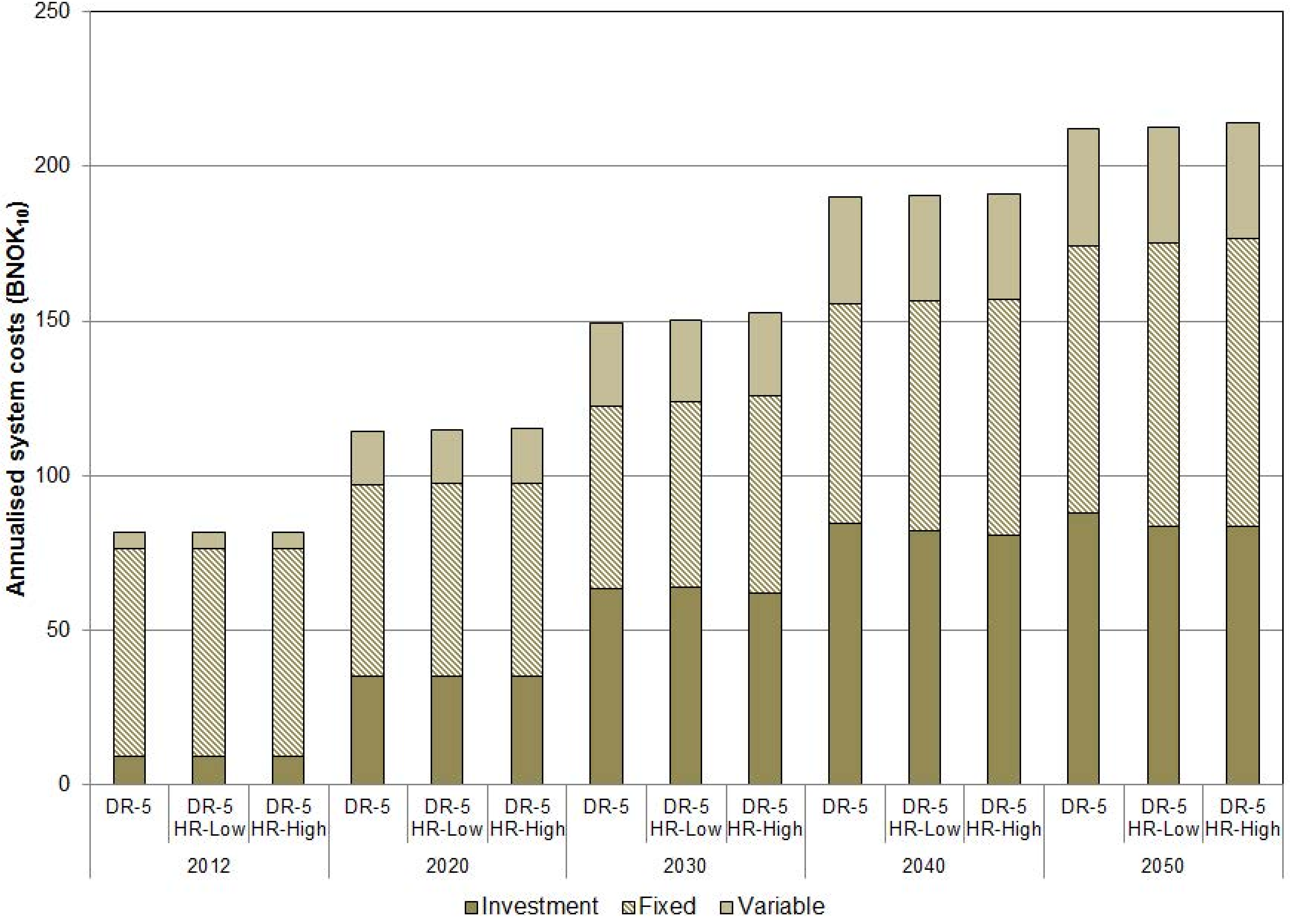


Electricity trade in Norway (TWh)
0
10
20
30
40
50
60
DR-5
DR-15
2012
2020
2030
2040
2050
Export
Import


Electricity production in Norway (TWh)
200
180
160
140
120
100
80
60
40
20
0
DR-5
DR-5 HR-Low
DR-5 HR-High
DR-5
DR-5 HR-Low
DR-5 HR-High
DR-5
DR-5 HR-Low
DR-5 HR-High
DR-5
DR-5 HR-Low
DR-5 HR-High
DR-5
DR-5 HR-Low
DR-5 HR-High
2012
2020
2030
2040
2050
Natural Gas
Hydro Dam I
Hydro RoR I
Hydro Dam II
Hydro RoR II
Hydro RoR III
Wind Onshore
Wind Offshore


Electricity trade in Norway (TWh)
0
10
20
30
40
50
60
DR-5
DR-5 HR-Low
DR-5 HR-High
2012
2020
2030
2040
2050
Export
Import


Annualised system costs (BNOK$_{10}$)
300
250
200
150
100
50
0
DR-5
DR-15
DR-5
DR-15
DR-5
DR-15
DR-5
DR-15
DR-5
DR-15
2012
2020
2030
2040
2050
Investment
Fixed
Variable


Annualised system costs (BNOK$_{10}$)
250
200
150
100
50
0
DR-5
DR-5 HR-Low
DR-5 HR-High
2012
DR-5
DR-5 HR-Low
DR-5 HR-High
2020
DR-5
DR-5 HR-Low
DR-5 HR-High
2030
DR-5
DR-5 HR-Low
DR-5 HR-High
2040
DR-5
DR-5 HR-Low
DR-5 HR-High
2050
Investment
Fixed
Variable