Autarky penalty versus system cost effects for Europe of large-scale renewable energy imports from North Africa

Dalla Longa, F.; van der Zwaan, B.

DOI
10.1016/j.esr.2023.101289

Publication date
2024

Document Version
Final published version

Published in
Energy Strategy Reviews

License
CC BY

Energy Strategy Reviews 51 (2024) 101289

Contents lists available at ScienceDirect

Energy Strategy Reviews

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

Autarky penalty versus system cost effects for Europe of large-scale renewable energy imports from North Africa

Francesco Dalla Longa [a], Bob van der Zwaan [a,b,c,*]

[a] TNO, Energy Transition Studies (ETS), Amsterdam, the Netherlands
[b] University of Amsterdam, Faculty of Science (HIMS and IAS), Amsterdam, the Netherlands
[c] Johns Hopkins University, School of Advanced International Studies (SAIS), Bologna, Italy

ARTICLE INFO

Handling Editor: Xi Lu

Keywords:
Energy partnership
Renewables trade
Electricity
Hydrogen
Autarky penalty

ABSTRACT

We quantify in more detail than earlier studies the cost trade-offs of establishing import-export links between Europe and North Africa for two quintessential energy carriers needed for the energy transition: electricity and hydrogen. Using the TIAM-ECN model, we show under what assumptions Europe will make a net energy system cost gain or, inversely, pay a net price for exploiting such interlinkages. We find that allowing for trade of renewable energy between Europe and North Africa substantially reduces the EU's domestic renewable energy capacity investments needed to implement its Green Deal and Fit for 55 Programme. In addition to creating import-export scenarios for electricity and hydrogen across the Mediterranean and investigating the cost implications of a European-African energy partnership until 2050, we perform a detailed sensitivity analysis regarding possible technological developments and sectoral shifts, as well as vis-à-vis potential cost, sectoral and technical asymmetries between Europe and North Africa. We introduce a new concept in energy analysis, autarky penalty, which is the price paid by a region for restricting energy trade with its neighbors. If domestic hydrogen production from solar and wind energy through electrolysis is constrained, Europe's autarky penalty may increase to 30 billion $ annually by 2050.

1. Introduction

Three main topics have recently shaped the European energy transition debate and are strongly influencing the implementation of the EU's Green Deal for decades to come: (1) an exponential increase in the prospects of hydrogen as future climate-friendly energy carrier in several sectors of the European economy; (2) a revival of energy security concerns on the political agenda of many European countries against faltering supplies of natural gas from Russia following its invasion of Ukraine; and (3) low-carbon climate-resilient development in Africa through large-scale renewable energy deployment and, consequently, its enormous potential to export renewables across the world, notably to Europe.

It is becoming increasingly apparent that hydrogen is likely to play a significant role in a broad range of applications, including in industry, transportation, and the residential & commercial sectors. Since hydrogen can be produced in low-carbon supply processes, it can contribute to global climate change control, and its costs are projected to decline substantially over the years to come [1]. The rise of hydrogen as energy carrier of the future is confirmed by a flood of scientific publications on hydrogen-related topics as well as reports from international organizations such as IRENA on subjects like innovation trends in electrolysers, potential for global hydrogen trade, hydrogen carrier types, green hydrogen costs and potentials, and the geopolitical dimensions of hydrogen use [2–10].

The war in Ukraine and ensuing economic sanctions that the West imposed on Russia has led Russia to cut natural gas exports to Europe, and the EU to terminate its dependency on imports from Russia of all fossil fuels. Subsequently, for the near term, the EU has started to search for alternative sources of, most importantly, natural gas from notably the US and the Middle East. For the mid and longer term, it has adopted a strategy to more aggressively stimulate the diversification of all its energy imports as well as the acceleration of an expansion of domestic renewable energy production. In this process, the EU needs to carefully consider whether old energy dependencies are not going to be replaced by new ones, not just for traditional fossil fuels that gradually need to be phased out, but also for renewables based energy carriers and technologies, whether e.g. renewable hydrogen or the materials used for solar

* Corresponding author. TNO, Energy Transition Studies (ETS), Amsterdam, the Netherlands.
E-mail address: bob.vanderzwaan@tno.nl (B. van der Zwaan).

https://doi.org/10.1016/j.esr.2023.101289
Received 6 November 2022; Received in revised form 4 December 2023; Accepted 26 December 2023
Available online 3 January 2024

panel manufacturing. Yet, it is becoming clear that amidst the process of alteration and diversification of Europe's energy trade, imports of renewable energy are going to play an increasingly substantial role in the European energy transition.

In parallel to these developments in Europe, a renewable energy transition in Africa is critical for a pathway towards a prosperous and sustainable Africa [11,12]. Since most energy infrastructure is still to be built in Africa in order to bring its energy needs on par with existing infrastructure in Europe, it is actually not so much a matter of energy transition, but of development that ought to be low-carbon across all stages and in all sectors right from today's starting point. It has been pointed out in integrated assessment studies of scenarios for low-carbon development that Africa could largely leap-frog the use of fossil fuels and kick-off its itinerary towards prosperity by relying predominantly on renewable forms of energy (such as in Ref. [13]).

The topic of renewable electricity and hydrogen production in North Africa and exports thereof to Europe is at the intersection of the three key axes listed above of the current strategic and political energy debate in the EU. The subject deserves in-depth analysis from many different angles, and an expanding set of studies is therefore dedicated to it. The present paper builds on and enlarges this literature, by describing the outcomes of recent energy system research that provides a detailed integrated assessment and cost perspective of this subject matter. The role and trade of hydrogen in future energy systems have recently become prominent subjects in the energy and climate change mitigation literature. For instance, Ref. [14] devised a global hydrogen market model and identified European countries as likely future importers of hydrogen. Their analysis of least-cost hydrogen technologies highlights that a mix of renewable-based and fossil-fuel-based hydrogen production is likely to arise across the globe; according to them, fossil-fuel-based hydrogen production may be the most economical option in several North African countries. In contrast, Ref. [15] found that North Africa possesses a remarkable potential for producing low-cost hydrogen based on solar and wind energy. Müller and Eichhammer [16] studied green hydrogen supply from the perspective of large-scale production facilities and capabilities; they found that, in North Africa, Tunisia already possesses much of the needed industrial know-how, more so than Algeria and Libya. With the present article we intend to further enrich the growing body of literature on the possibility of international hydrogen trade.

2. An energy partnership between Europe and North Africa

Only few experts doubt that hydrogen will play a critical role in multiple sectors to mitigate climate change. From a technical point of view North Africa is ideally situated to use its vast solar energy resources to produce renewable hydrogen. Apart from domestic usage, this hydrogen could be transported – either by pipelines or shipping – to other parts of the world including especially Europe. We do not yet know whether this makes sense from a financial point of view, since it is not trivial to estimate the costs of massive imports of hydrogen to Europe from North Africa. Pretty much the same applies for electricity, although for this energy carrier practical experience has been built already. The energy community has not yet figured out the implications of an energy partnership for these two energy carriers between Europe and North Africa, in terms of technology diffusion and sector impacts (not to speak of the more general geopolitical, institutional, social, and strategic considerations). In our previous work [17] we undertook a quantitative analysis of the possible economic and technological impacts of allowing for energy trade between Europe and North Africa. We performed our research with TIAM-ECN, an established integrated assessment model [18]. We thereby connected to earlier efforts to inspect the potential for (renewable) energy partnership between Europe and North Africa (see, for instance, Refs. [19–21]).

In our previous paper [17] we recalled that (the now former) Executive Vice-President of the European Commission, Frans Timmermans, supports creating an energy partnership with (North) Africa and installing a vast capacity of solar energy in Africa so as to transform it into hydrogen and import it into Europe [22]. We also observed that, because of differences in irradiation levels, it could indeed be more efficient to produce solar electricity and hydrogen in North Africa and import these energy carriers to Europe, rather than generating them at higher costs domestically in (North) Europe. From a global climate change mitigation point of view, exploiting such efficiencies is in principle profitable, since it allows to reduce overall renewable electricity capacity requirements. Yet the construction of this capacity in North Africa would imply costs associated with the infrastructure needed to transport electricity and hydrogen. We quantified the trade-off between the costs and benefits of establishing electricity and hydrogen import-export links between Europe and North Africa, and showed that for Europe a net price may have to be paid for exploiting such interlinkages, even while they reduce the domestic investments for renewable electricity capacity needed to implement the EU's Green Deal. In the present paper we enlarge our understanding of this outcome in much more detail, and determine under what conditions one also obtains a net cost benefit for Europe associated with a Europe-African energy partnership.

As demonstrated, for instance, by the sheer number of recent IRENA reports only, hydrogen is enjoying unprecedented strategic and political momentum. European gas infrastructure companies have reported plans for a European hydrogen network [23]. The EU has communicated its strategy on hydrogen in 2020 [24], outlining an enormous expansion in the production and consumption of hydrogen to meet its commitment of reaching climate neutrality by 2050 [25]. The EU's priority is the use of green hydrogen, produced from renewable electricity through electrolysis. Large amounts of renewable electricity are required to generate the desired volumes of renewable hydrogen. Costs, potential, and public acceptance of the required facilities within the EU create possible constraints to the envisaged quantity of renewable hydrogen that can be produced domestically. The EU therefore also contemplates imports of hydrogen produced elsewhere. The EU hydrogen strategy aims at developing 40 GW of electrolysers in Europe's neighborhood by 2030, in addition to 40 GW in the EU itself [24]. Northern Africa is a likely candidate for delivering low-cost renewable hydrogen, given its abundant potential of solar energy and vicinity to the EU [24,26,27].

The EU already imports large quantities of fossil fuels from Northern Africa. For example, approximately 1800 PJ of natural gas was imported in 2018 via pipelines and as liquified natural gas (LNG) from Algeria, Tunisia, and Libya to Spain and Italy (see Refs. [26,28] and 2019; [29]). Also Egypt once exported LNG to Europe, but exports halted in 2014 [30]. Discoveries of large gas fields in the Mediterranean could lead to Egypt re-entering the LNG export market in the near future [30]; van Wijk and Wouters, 2020). Also, electricity is traded between Europe and Northern Africa. Net exports of electricity take place from Spain to Morocco through the existing 1.4 GW connection [27,31,32]. Connections amounting to 4.6 GW are planned with as primary function to link solar energy projects in Tunisia and Libya to the electricity network in Italy and Greece [33]. Large projects such as the Mediterranean Solar Plan (MSP), DESERTEC, and MEDGRID were launched to promote the deployment of high voltage direct current (HVDC) connections for the transport of renewable electricity from North Africa to Europe, but these proposals have not been realized to date [21,34–37]. The chances of realizing an energy partnership between Europe and North Africa are now higher than in any of these earlier initiatives, given the current geopolitical circumstances and the envisaged role of renewable electricity and hydrogen in the European energy transition, hence the necessity to research them in more detail.

Most IAMs can be used to find cost-minimal energy systems, and a sub-set of them to explore realizations for establishing an energy partnership between Europe and North Africa. IAMs can be utilized to search for optimal balances between either producing relatively costly renewable electricity and hydrogen domestically, and, alternatively, letting these energy carriers being produced more cheaply abroad. The use of IAMs is central to the work by the IPCC (see, for example [38,39]), and a critical element of assisting policy design by notably the EC (2019). They are especially useful for studying the efforts needed to reach the goals of the Paris Agreement [40]. For this paper we therefore use an IAM to determine the costs and technology choices associated with varying levels of electricity and hydrogen generated in North Africa and imported into Europe.

Section 3 of this paper describes our research approach in terms of (i) the IAM that we use to investigate the subject of renewable energy trade between Europe and North Africa, (ii) the scenarios that we developed to undertake this analysis, and (iii) the sensitivity tests that we performed to scan a broad range of possible cost-optimal solutions. In section 4 we report our results regarding the cost implications of our scenarios and sensitivity tests for Europe and North Africa until 2050, as well as the electricity and hydrogen demand and supply impacts of these variations. In section 5 we discuss our findings and cast them in a broader perspective, while in section 6 we draw some overall conclusions and formulate recommendations for the policy making scene.

3. Energy system modeling

3.1. TIAM-ECN

TIAM-ECN, a member of the global family of IAMs, is the model that we employ for our analysis. It is a TIMES-based global bottom-up energy system model operated in the Energy Transition Studies (ETS) research group of TNO (formerly called ECN). TIAM-ECN is founded on the TIAM model, developed in 2008 under the assumption that the world is disaggregated into 15 regions, which over the years we expanded into a breakdown of 36 regions (for further details of the core model, including the equations behind its objective function, we refer to Ref. [41]; and [42]). TIAM is a linear optimization model simulating the development of the global energy economy from resource extraction to final energy use over a period of over 100 years. The objective function of TIAM-ECN is global and consists of the total discounted aggregated energy system costs calculated over the full time horizon summed across all 36 regions. Running scenarios with TIAM-ECN involves minimizing this objective function. TIAM-ECN thus allows for finding cost-minimal energy systems that meet the target of the Paris Agreement as well as constraints such as in terms of resource potentials and technology diffusion rates, and it calculates prices endogenously while matching energy demand and supply. Whereas the model is run for the world as a whole, it also enables the determination of optimal technology portfolios at the regional and (for some of the larger economies) national level.

As we wrote in Ref. [13]; the main cost components included in the objective function of TIAM-ECN are investment costs, fuel costs and fixed plus variable operation and maintenance (O&M) costs. Other cost components such as decommissioning and infrastructure costs are also included, albeit in a more simplified way. TIAM-ECN is based on a partial equilibrium approach with demand for energy services responding to changes in their respective prices through end-use price elasticities. Savings of energy demand and corresponding cost variations are thus accounted for in the objective function. The database associated with TIAM-ECN includes several hundreds of technologies for a broad set of different sectors including industry, transportation, electricity generation, and the commercial and residential sector. For a general description of the reference energy system behind TIAM-ECN, see Ref. [43].

We cannot possibly reiterate here the rest of the main features of TIAM-ECN; for a more detailed description we refer to previous studies (e.g. Refs. [13,44–46]). Several recent publications were dedicated to energy and climate change issues in Africa (see, for instance, Refs. [13,47]). We build on that work and use the updates that were performed for Africa under the Horizon-2020 TRANSRISK project [13,48] for analyzing energy trade opportunities between Europe and North Africa. We also substantially benefit from the research undertaken in 2021 on a possible European-African energy partnership in a project supported by the Ministry of Economic Affairs and Climate Policy of the Netherlands [17].

For the purpose of the present work, the set-up of TIAM-ECN includes a representation of North Africa defined as the cluster of 5 Maghreb countries, which are distinct entities in TIAM-ECN. Europe is *grosso modo* equivalent to Western Europe, which in TIAM-ECN entails a group of European countries (see Ref. [46] with an energy mix that is representative of that of the member states of the EU-27. East Europe is excluded for this study, since – for trade of energy carriers with North Africa – East European nations are probably not going to play a substantial role in the foreseeable future. Solar photovoltaic and solar thermal energy is the likeliest source for producing renewable electricity and hydrogen in North Africa. We also include other electricity and hydrogen production opportunities, to yield a broad view on trade possibilities between Europe and North Africa. Hence, also wind energy is simulated (Morocco, for instance, possesses a relatively large wind energy potential). Various biomass alternatives are not considered in North Africa, because we do not think that they can readily compete with low-cost solar energy resources (or with biomass energy products from other regions, such as Latin America) and since the availability of water and nutrients is constrained in North Africa. In the last column of Table 1 in Ref. [17]; we reported the average availability factors that we adopted for notably solar energy in our TIAM-ECN scenario runs. The solar irradiance conditions are such that the availability factor for PV technology is on average higher in North Africa than in Europe. This high availability factor (AF) leads to correspondingly lower electricity and hydrogen generation costs. Hence, while the basic technology costs (CAPEX for capital expenditures, and OPEX for operation and maintenance (O&M) expenditures) are assumed to be the same in our reference scenario for our two regions, the big differentiating parameter is the AF. We assume that the AF on an average summer day for PV-electrolysis in Europe is 0.30, while in North Africa it is 0.52, which translates directly in a proportional impact on the levelized cost of electricity (LCOE). Since TIAM-ECN is a global model with 36 regions (see Ref. [13]), Europe can of course also trade fossil fuels, biomass and electricity with regions other than North Africa.

3.2. Scenarios

For the present analysis we use two of the scenarios that we developed in our previous work on an electricity and hydrogen partnership between Europe and North Africa [17] – named Autarkic and Efficient – for reasons of consistency and because the purpose of the current study is to test the robustness of our earlier findings under a range of changes in our underlying assumptions. As before, in both scenarios we assume climate mitigation efforts in line with the goals of the Paris Agreement (COP-21, 2015) and adopt net-zero greenhouse gas emissions in Europe by 2050, since this is the EU's formal policy target under its Green Deal and Fit for 55 package [25,49]. For the world as a whole we adopt an exogenous constraint that implies greenhouse gas emissions to remain on a trajectory compatible with a global 2 °C target; this is implemented as a global carbon budget over the period 2016 to 2050 of 850 $GtCO_2$. Table 1 summarizes the main features of our scenarios for energy trade between Europe and North Africa, aggregated over the five Maghreb

Table 1
Summary of scenarios for energy trade between North Africa and Europe.

Scenario	Electricity import (2030–2050)	Hydrogen import (2030–2050)	2 °C policy
Autarkic	Low *(6 GW)*	None *(0 PJ/yr)*	Yes
Efficient	High *(no limit)*	High *(max 250–3750 PJ/yr)*	Yes

N.B. Numbers are aggregated across the 5 Maghreb countries.

countries (see Table A1 in the appendix of [17] for numbers for each of these countries as well as their justification).

In the Autarkic scenario we assume low imports for both electricity and hydrogen. For electricity we impose an upper limit for trade between Europe and North Africa of 6 GW until 2050, which corresponds to the capacity of interconnections currently in operation and/or planned between the two continents (see Ref. [33]. For hydrogen we adopt no trade at all, hence a continuation of the current situation. In the Efficient scenario we allow for high imports of both energy carriers. For electricity we apply no trade limit, so that TIAM-ECN calculates an optimum for electricity production levels and the localization thereof. This optimum is determined independent of constraints that may exist in reality but that the model is unable to represent (think of e.g. resource, geopolitical, legislative and regulatory limitations or shortcomings). For hydrogen trade we adopt an upper limit that increases from 250 PJ/yr in 2030–3750 PJ/yr in 2050, corresponding to 2 and 32 MtH_2/yr respectively. As thoroughly described in our previous work [17], these numbers are scenario assumptions that are inspired by expected near-term capacity for natural gas trade between North Africa and Europe. Running TIAM-ECN yields scenarios that are projections of the energy system in the future under the objective function's cost-minimization principle. These scenarios are thus optimization outcomes under a plethora of assumptions that could be realized in practice. We emphasize once more, as we have done in many of our previous publications, that scenarios with TIAM-ECN – and with any other energy system or integrated assessment model for that matter – are by no means predictions.

3.3. Sensitivity tests

Table 2 shows a summary of the 6 sensitivity tests that we performed for this research. All 6 of these tests are undertaken against the base case, which refers to the central parameter assumptions adopted for the Autarkic and Efficient scenarios (the base case assumptions are the same for these two scenarios, apart from the electricity and hydrogen import limits reported in Table 1). In the first sensitivity test the CAPEX of electrolysis in North Africa is lowered by 50 % from the base case values of 39.52 and 11.37 M$/PJ/yr in 2020 and 2050 respectively. In the base case these values applied to both Europe and North Africa, while under this sensitivity test it is assumed that in North Africa investment cost reductions are achieved as a result of, for instance, exceptional economies-of-scale and low labor costs. In the second sensitivity test we implement a different assumption regarding the distribution of pipeline and grid infrastructure costs. In the base case we adopted an equal sharing of these costs between Europe and North Africa, while under this sensitivity test it is assumed that all infrastructure related costs incurred as a result of transporting energy carriers between the two continents are attributed to Europe. In the third sensitivity test we strongly limit the spread of hydrogen as energy carrier in road transport in Europe. In the base case, TIAM-ECN determines a quite optimistic diffusion of hydrogen in vehicles like cars, trucks and buses towards 2050, but under this sensitivity test we adopt a maximum share of hydrogen in European road transport of 5 % in 2040 and 15 % in 2050. In the fourth sensitivity test we assume that the costs of battery electric vehicles (BEVs) are 25 % lower than the cost reductions we adopt for these vehicles until 2050 in the base case. In 2020 the range of the average costs of regular electric cars was $30000 to $40000 and in the base case we took the upper of these values (to reflect, for instance, the costs of luxury cars and account for the mismatch between the lifetime of cars versus that of batteries), while in this sensitivity test we took the lower value of this range to simulate a more optimistic development for BEVs. In the fifth sensitivity test we allow for a higher share of hydrogen being transportable through the existing European natural gas grid. In the base case we assumed that the natural gas network could contain up to 15 % of hydrogen, while under this sensitivity test we increase the upper limit to a share of 85 %. In the sixth sensitivity test we assume that the potential to produce renewable hydrogen in Europe from PV and wind resources is reduced with respect to the base case, for example as a result of space constraints or limited public acceptance for large-scale solar and wind parks equipped with electrolysers. Whereas in the base case a relatively optimistic diffusion of hydrogen from PV and wind energy materializes, under this sensitivity test we introduce a ceiling for renewable hydrogen production at 85 % below the base case level until 2050.

Table 2
Summary of sensitivity tests.

	Name	Description
1	Electrolysis CAPEX asymmetry	CAPEX of electrolysis is 50 % lower in North Africa than in Europe
2	Infrastructure cost asymmetry	Electricity and hydrogen trade infrastructure costs are fully borne by Europe
3	Limited H_2 in EU road transport	The maximum share of H_2 in European road transport is 5 % in 2040 and 15 % in 2050
4	Steeper cost reductions for BEVs	Costs of BEVs reduce by an additional 25 %: lower limit of current cost range
5	High H_2 share in EU gas network	Existing gas network in Europe is upgraded to allow for carrying 85 % H_2 share instead of 15 %
6	Limited REN H_2 production in EU	H_2 production from PV and wind in Europe is reduced by 85 % w.r.t. the base case

For all the 6 sensitivity tests, we run an Autarkic and an Efficient scenario variant, i.e. adopting – alongside the assumptions reported in Table 2 – the respective electricity and hydrogen import constraints of Table 1. In this manner we are able to inspect the differences that an Autarkic vs. an Efficient scenario might trigger for the European and North African energy systems under a set of 6 diverse sensitivity assumptions.

4. Results

On a global multi-regional level, additional energy system costs are incurred when switching from the Efficient to the Autarkic scenario. Below, we refer to these extra system costs as the Autarky Penalty (AP). Essentially, AP is the price for 'going solo'. Usually, a positive value of AP at the global or joint (multi-regional) level translates into positive AP values at the level of individual regions, but we showed in Ref. [17] that this may not always necessarily hold, such as in our present case for Europe. Fig. 1 shows our AP calculations in the base case, as well as for our six sensitivity tests. In the base case, as we saw before, the net overall AP for Europe and North Africa together (indicated by an open circle) amounts to little over 20 G$/yr in 2050, but this joint value is the resultant of an AP of slightly less than 40 G$/yr for Africa and a value close to −20 G$/yr for Europe. Consequently, Europe pays a price for the energy partnership realized between Europe and North Africa in the optimal solution for the unconstrained 'Efficient' scenario. This was one of our notable findings with which we ended our previous study [17].

When the CAPEX of electrolysis becomes 50 % lower in North Africa than in Europe, as in the first sensitivity test, we see that the net overall AP nearly doubles, as a result of North Africa's AP substantially increasing and Europe's AP turning less negative. If the electricity and hydrogen trade infrastructure costs are fully borne by Europe, rather than equally shared by the two regions, as under the second sensitivity test, we observe that the net overall AP is nearly the same as in the base case, but under regional values for the AP that are higher for North Africa and more negative for Europe. When the share of H_2 in European road transport is heavily constrained, we observe a reduction in the value of the net overall AP down to a level of less than 20 G$/yr in 2050, the resultant of an AP of around 25 G$/yr for Africa and some −8 G$/yr for Europe. If the costs of BEVs reduce by an additional 25 %, we obtain a net overall AP as low as approximately 12 G$/yr in 2050, based on an AP of over 35 G$/yr for Africa and close to −25 G$/yr for Europe. Upgrading the existing natural gas network in Europe to allow for a share of 85 % H_2 yields a relatively high net overall AP of close to 30 G$/yr, with a higher regional AP in North Africa and an approximately

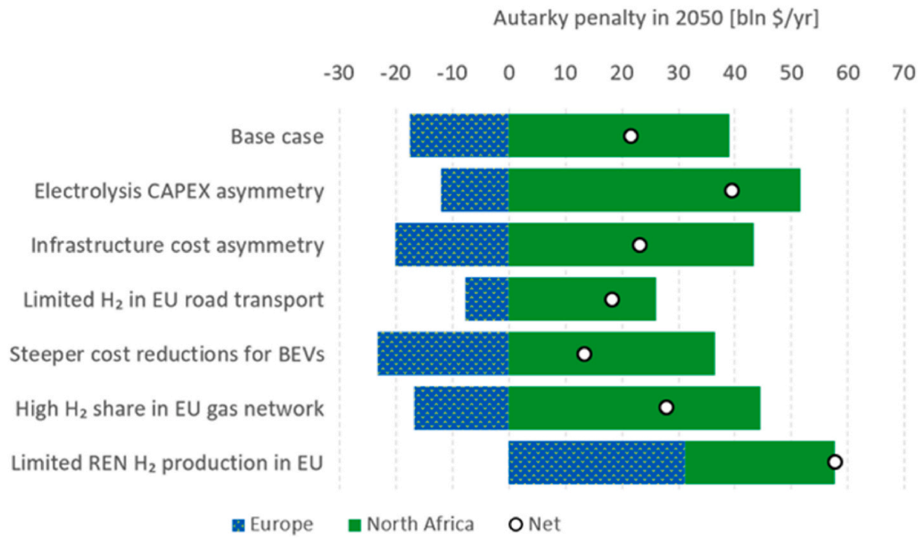

Fig. 1. Sensitivity test for the joint autarky penalty in 2050, calculated with TIAM-ECN, with break-down into regional autarky penalties for Europe and North Africa.

equal one for Europe in comparison to the base case. The largest change occurs when we drastically reduce H_2 production from PV and wind in Europe: this is the only sensitivity test under which the regional values of AP for both North Africa and Europe become positive, with a net overall AP of almost 60 G$/yr, nearly three times higher than in the base case.

Let us now have a closer look at the origins of these impacts under our six sensitivity tests. Fig. 2 presents our sensitivity calculations for the regional autarky penalty in 2050 for Europe and North Africa with a break-down into the main cost components: variable OPEX, fixed OPEX, CAPEX and trade costs. In the upper plot of this Figure, for Europe, we see that the negative values of its AP derive essentially from the large costs associated with trade between North Africa and Europe, which outshadow the additional costs that are incurred in terms of CAPEX and fixed OPEX in the Autarky scenario. When the use of H_2 in the European road transport sector is limited, we obtain an AP quite close to zero. Only when the use of renewable energy like solar and wind power is strongly constrained in Europe for H_2 production, we get a positive AP value. The reason is that, once domestic European H_2 generation is largely off the table, Europe is obliged to import it from outside its borders or rather, as we will see, it may import fossil fuels from abroad and transform these into H_2 in combination with carbon dioxide capture and storage (CCS). The price of going autarkic then is high, since importing H_2 from North Africa is much more affordable than getting it (either directly or in the form of energy carriers like fossil fuels) from other, more distant, locations. The lower plot of this Figure, for North Africa, is pretty much the

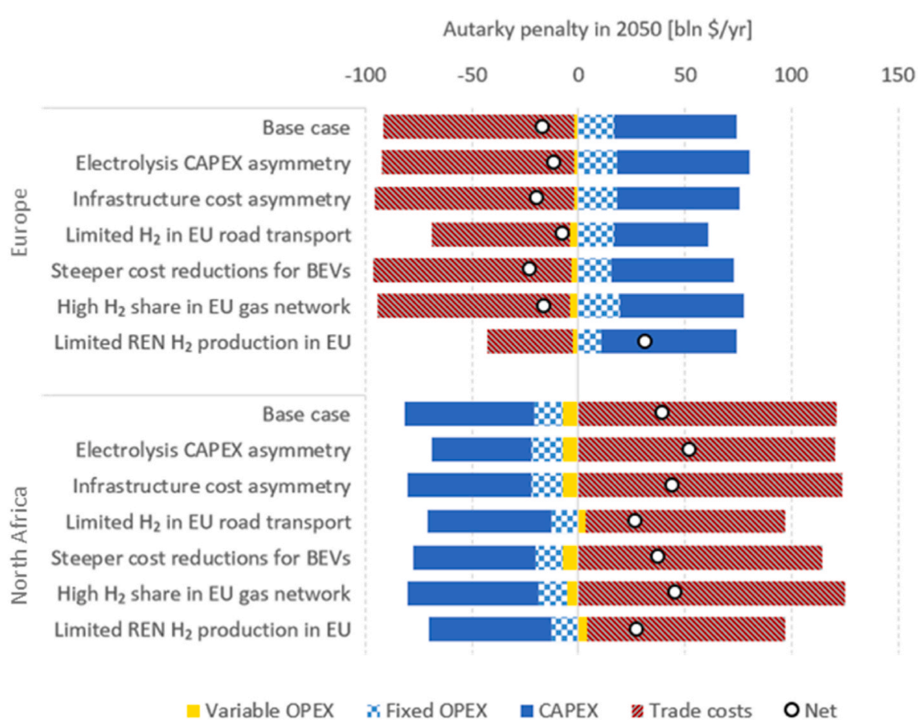

Fig. 2. Sensitivity test for the regional autarky penalties in 2050 for Europe and North Africa, calculated with TIAM-ECN, with break-down into main cost components.

mirror image of that for Europe. The AP is always positive for North Africa, under all sensitivity tests, since it loses the gains from trade when no energy partnership is established between the two continents. These losses are larger than the gains it makes in obviating the need for large costs associated with CAPEX and fixed OPEX for corresponding domestic North African energy projects. We observe the lowest positive values for the regional AP of North Africa when either the use of H_2 in the European road transport sector is constrained or when there is limited availability of solar and wind energy capacity in Europe for electrolysis-driven H_2 production. The explanation is that in these two cases, in partial response to reduced domestic H_2 usage or availability, Europe switches to enhanced usage of energy carriers other than H_2. Consequently, this lowers the trade of H_2 even in the efficient scenario, hence reduces the regional AP for North Africa.

In Fig. 3 we specify the break-down of the changes in net CAPEX value for Europe in 2050. The net numbers indicated by open circles in Fig. 3 correspond to the length of the blue bars in the upper plot of Fig. 2. Autarky yields more investments in energy infrastructure domestically, hence the positive contributions to the European AP from both electricity and hydrogen related CAPEX. Likewise, under autarky conditions, Europe makes additional investments in energy demand reduction, hence the positive contribution to the AP from CAPEX in savings technology. Inversely, the savings created by a reduced energy demand yield a negative contribution to the European AP from CAPEX of demand-side technologies. Autarky implies diminished imports of electricity and hydrogen from North Africa into Europe, hence a reduction in trade infrastructure related CAPEX requirements. In all sensitivity tests, the positive contributions to the AP largely outweigh the negative ones, hence changes in the net CAPEX value invariably contribute positively to the European AP. In sensitivity tests 3 and 5 BEVs are more widely spread than in the other cases (except in comparison to test 4, in which they diffuse even more), either because the use of hydrogen in Europe's road transport sector is limited (test 3) or because a high share of hydrogen in the European gas network diverts much of the hydrogen to the commercial, residential and industrial sectors (test 5). The relatively large savings CAPEX contributions under these two sensitivity tests lead to sizeable gains on the demand-side CAPEX, as the model choses to reduce the number of BEVs when going autarkic. The relatively large contribution to the European AP from electricity production CAPEX under sensitivity test 5 results from an increased deployment of notably wind power when going autarkic (see also Fig. A5). In sensitivity test 6, we see from Fig. 3 that the relatively large positive contribution to the European AP from savings CAPEX on the supply side is matched with a quite small negative contribution from demand-side CAPEX, since in this case the model choses to reduce the number of other (cheaper) demand-side technologies than that of costly BEVs to compensate for the savings on the supply side.

In Fig. 4 we specify the break-down of the changes in net trade costs for Europe in 2050. The net numbers indicated by open circles in Fig. 4 correspond to the length of the red bars in the upper plot of Fig. 2. Autarky implies a strong reduction of imports from North Africa into Europe of electricity and hydrogen, which obviates the trade costs associated with these energy carriers. Hence, we observe a negative contribution to the European AP from the costs of trade of electricity and hydrogen. The reduction in trade of these two energy carriers necessitates an increase of imports of fossil fuels, which are partly used for domestic H_2 production in Europe in combination with CCS. Consequently, the costs associated with the trade of fossil fuels – principally oil and natural gas, but in the last sensitivity test also coal – deliver a positive contribution to the European AP. As one can see, a change in biomass trade plays no role of significance in Fig. 4, since the positive contribution to the European AP from an increase of biomass imports from abroad is hardly discernible. In all sensitivity tests, the negative contributions to the AP largely outweigh the positive ones, hence changes in the net trade costs invariably contribute negatively to the European AP. A few more observations can be made with regards to Fig. 4. In three of the sensitivity tests (3, 5 and 6) we see a particularly large positive contribution to the European AP from oil trade expenditures, especially when the use of hydrogen in Europe's road transport sector is limited (test 3) and when there is limited availability of renewables for green hydrogen production in Europe through electrolysis of water (test 6). We find that this is not the result of increased oil import levels from e.g. the Middle East when Europe and North Africa obviate energy trade relations, but of an increase of oil prices, which are endogenously determined in TIAM-ECN. Under autarky and limited availability of solar and wind energy for domestic hydrogen production in Europe (test 6) we see a strong increase of coal imports from third countries: this coal is almost solely used in European domestic H_2 production in combination with CCS. Under sensitivity test 3 we see a contribution from electricity to the trade cost breakdown that is somewhat smaller than in the other tests (1 through 5), which we find is essentially an endogenous price effect. Under sensitivity test 6 we see that the contribution from electricity is even further reduced, which is a reflection of the fact that in this sensitivity case – already in the Efficient scenario – relatively more electricity is imported into Europe from regions other than North Africa for the purpose of domestic hydrogen generation. Hence a change from the Efficient to Autarkic scenario impacts less the electricity trade from North Africa to Europe, which is expressed as a reduction of the electricity bar in Fig. 4.

We next gather the information depicted for Europe in Figs. 2–4, and visualize it jointly in 'waterfall' graphs for the European AP. In Fig. 5 we

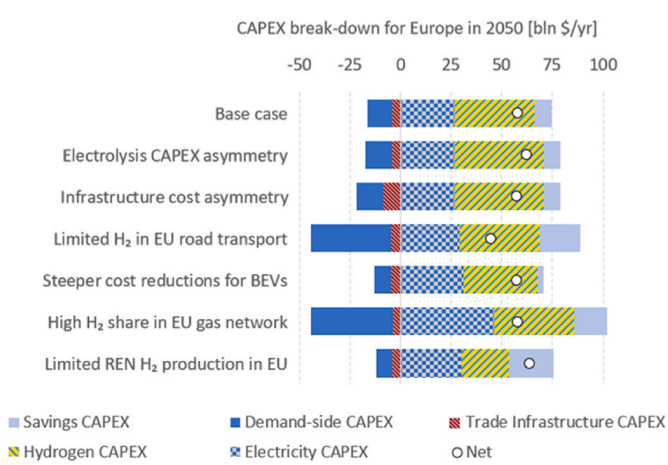

Fig. 3. Sensitivity test for break-down of net CAPEX values calculated with TIAM-ECN for Europe in 2050.

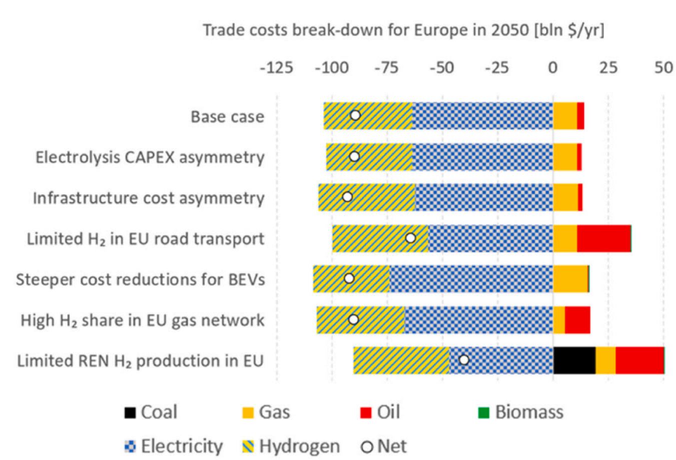

Fig. 4. Sensitivity test for break-down of net trade costs calculated with TIAM-ECN for Europe in 2050.

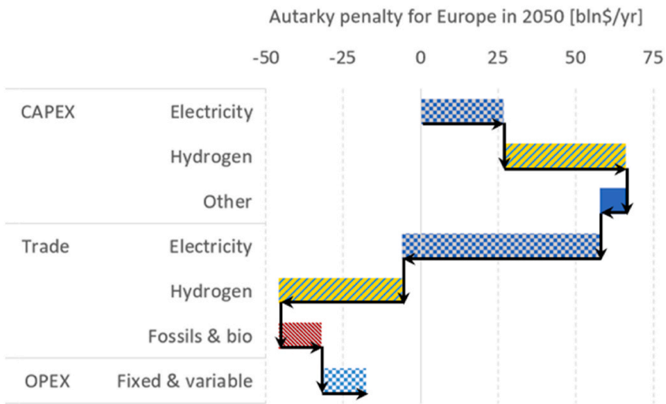

Fig. 5. Break-down of the autarky penalty calculated with TIAM-ECN for Europe in 2050: base case.

do this, first of all, for the base case, showing the complete break-down of the European AP. As Fig. 5 shows, increased CAPEX for electricity and hydrogen production yields positive contributions to the European AP, while the change in remaining ('other') CAPEX (resulting from changes in savings, demand-side and trade infrastructure CAPEX) delivers a relatively small negative contribution. A drop in trade of electricity and hydrogen generates negative contributions to the European AP, while a slight increase in trade of fossil fuels does the reverse. Because of an increase in domestic production of electricity and hydrogen, O&M costs augment, which leads to a (relatively limited) positive contribution from (fixed and variable) OPEX to the European AP.

Fig. 6 shows another 'waterfall' graph for the European AP, but now for the last of our six sensitivity tests, in which we strongly limit the domestic production of H_2 through solar and wind power. For this "limited REN H_2 production in EU" sensitivity test, Fig. 6 visualizes the complete break-down of the European AP. Like with Fig. 5, an increase in CAPEX for electricity and hydrogen production yields positive contributions to the European AP. Here, however, the change in other CAPEX also delivers a small positive contribution. The reason is that under strong domestic H_2 production limitations a switch to autarky provokes an increase in investments in savings technology large enough to outweigh reductions in demand-side and trade infrastructure investments. Like in Fig. 5 for the base case, a drop in trade of electricity and hydrogen generates negative contributions to the European AP, but an increase in trade of fossil fuels has the opposite effect. The rise in fossil fuel expenditures in this sensitivity test is much larger, however, than in the base case and under the other tests, in order to compensate for the heavily constrained availability of domestically generated

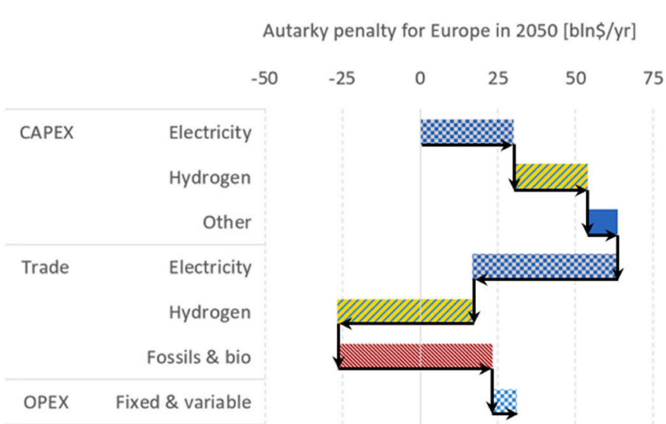

Fig. 6. Break-down of the autarky penalty calculated with TIAM-ECN for Europe in 2050: sensitivity test with limited domestic production of renewable H_2.

renewable hydrogen. As with the base case, as a result of an increase in domestic production of electricity and hydrogen, O&M costs become higher, which leads to a small positive contribution from OPEX to the European AP.

The present study focuses first and foremost on the European side of a possible European–North African energy partnership, since we dedicated our earlier publication [17] equally to both sides of the subject matter. Yet for the sake of completeness we report in the online Support Information (SI) file attached to the present article the equivalent plots to Figs. 3–6 but applied to North Africa. In the same SI file we include Figures for the break-down of electricity and hydrogen supply as well as usage for both Europe and North Africa in 2050.

5. Discussion

Interestingly, the results reported in the previous section were the ones that we speculated on in our previous paper [17]. We ended that paper by stating that even when Europe needed to pay a net price for establishing an energy trade partnership with North Africa, it could still be worth considering it, because of a number of important reasons. Indeed, we argued that Europe, despite potential fears over being subjected to high energy trade costs and becoming vulnerable for new energy dependencies, should seriously consider an energy partnership with North Africa, not only because of the associated increase in overall climate change mitigation efficiency that can be realized, but also since trade revenues for North African countries can lead to a series of positive socio-economic effects in the region, thereby possibly enhancing local political stability, and potentially even containing future (climate-and/or conflict-related) refugee streams from North Africa – a theme high on the EU's political agenda that can benefit from a strategic energy partnership. Another reason for Europe perhaps wanting to place renewable energy and hydrogen production, which demands abundant space, outside its borders is that it could thereby obviate the difficult task of finding suitable locations under often stringent land availability constraints and strict regulatory environments. Yet in the present paper we have proven that precisely when limited space availability leads to restrictions on the amounts of renewable hydrogen that Europe can generate domestically, it becomes economically profitable to allow for extensive imports of renewable electricity and hydrogen from North Africa. Indeed, in that case the European autarky penalty is positive, as we have demonstrated in Fig. 6.

Fig. 6 also shows the break-down of the autarky penalty calculated with TIAM-ECN for Europe in 2050, that is, it explains how the positive value of the autarky penalty is obtained through contributions from the various major cost components, or rather changes therein when switching from the Efficient to the Autarkic scenario. Fig. 6 thus reports the answers to one of our central research questions in this paper: under what conditions does the autarky penalty for Europe turn positive? Interestingly, in the other sensitivity tests that we undertook – we actually performed many more than the ones we showed here, but the others show no additional insights from the main tendencies that we observe in these six tests – the European AP remains negative. That in itself is a rather remarkable finding. It is our hope that – inspired by our present paper – other researchers perform analogous studies using alternative energy system models, thereby testing the robustness of our findings using model formulations that are different from that of TIAM-ECN. For future work, we thus propose that we subject the sign and value of the autarky penalty, both at the global and regional level for Europe and North Africa, to a cross-model comparison study, in which several energy system models are subjected to the same scenario protocol.

We want to take away a common confusion, which we have experienced a few times when presenting our findings to various types of audiences. An automatic reaction sometimes proved to be that, if domestic electricity and hydrogen production is more expensive than the generation of these energy carriers abroad, making a shift from local to foreign production makes sense as long as the extra costs from additional trade infrastructural requirements do not outweigh the generation cost gains associated with the shift. This first impression, however, is wrong and the reason why is quite simple. Formulated in a different way: since electricity and hydrogen can be generated in North Africa at lower costs than in Europe, one might expect that importing these carriers from North Africa would always (under relatively low transmission and transportation costs) be cheaper for Europe than producing them domestically – yet our results reveal that this expectation is not so straightforward.

The use of less costly foreign electricity and hydrogen production results in lower overall costs for the combined European and North African energy system. The electricity and hydrogen trade ensuing from this cost reduction, however, implies additional costs for Europe (the buyer) and gains for North Africa (the seller). Under relatively high electricity and hydrogen market prices, these additional costs for Europe may exceed local renewable CAPEX savings, and hence trigger a negative autarky penalty. This is indeed the case in all sensitivity tests that we analyzed with TIAM-ECN, with the exception of the last one, in which the limited availability of domestic renewable resources for hydrogen generation in Europe renders the import of energy carriers from North Africa necessary. Energy carrier prices are calculated endogenously in TIAM-ECN, and they are determined by supply-demand equilibrium (see Ref. [50]). In the future it would be interesting to explore the robustness of our outcomes under fixed (low) import price regimes, for example in the context of a partnership between Europe and North Africa in which the price of electricity and hydrogen is negotiated and agreed upon in a contractual form instead of being purely decided by market forces.

The decrease in BEV deployment in the Autarkic version of scenario tests 3 and 5 with respect to their Efficient counterparts, as well as the relatively larger contribution of hydrogen versus electricity in the transport sector (see e.g. Figs A5 and A6), deserves further analysis. At the time of writing, electricity appears as a more readily implementable alternative energy carrier for the transport sector than hydrogen. This is mainly a consequence of the relatively low overall costs and ubiquity of electricity-powered vehicles (for road, rail and water-based transportation) and the readily implementable infrastructure (at least in Europe, thanks to a refined power grid and availability of charging stations). Hydrogen-based transport, on the other hand, is currently more expensive and the needed infrastructure is still largely lacking. While we take into account the time dimension of the implementation of different infrastructures in our scenarios, we acknowledge that a thorough review of the costs and potentials of various alternative energy carriers for the whole transport sector (including synthetic and bio-based fuels, apart from electricity and hydrogen) should be carried out to ascertain that hydrogen demand in Europe is not overestimated in our analysis, as perhaps presently is the case. We leave this for a future study, given the observation that our hydrogen demand projections for Europe are well-aligned with the recent literature on this subject by, amongst others, IRENA (see references listed in the Introduction). Also, our scenario variants with reduced hydrogen use in the transport sector (i.e. tests 3 and 6) adequately illustrate a realistic deployment of hydrogen across sectors.

For our future research activities we plan to expand the present study along at least a few important lines. First, we intend to extend our analysis to also cover the Middle East. This is not only because Europe is currently increasingly exploring the possibilities of intensifying imports of natural gas from this region, but also since the Middle East's extensive solar energy resources renders it a potential large exporter of renewably produced hydrogen. Second, and directly connected to the first point, we would like to implement in TIAM-ECN the possibility of transporting hydrogen in a liquid state through specially designed ships, whereby we complement our current simulation of transporting it through pipelines. This is particularly pertinent for imports of hydrogen into Europe from larger distances, such as from the Middle East, for which the benefits of shipping may outshadow those of pipelining hydrogen on the basis of cost, geopolitical, practical and technical arguments. Third, we intend to modify our scenarios and the technology & sector assumptions underlying them. In particular, our new base case will reflect the parameter variations that we undertook under the present paper's six sensitivity tests, notably the one that reflects limited availability of solar and wind energy for domestic hydrogen production in Europe, for the reasons specified above. Under these assumptions, our new scenario definitions will allow for inspecting variations in natural gas delivery to Europe from Russia, as well as varying partnership assumptions between Europe, on the one hand, and regions like the Middle East and North Africa, on the other hand.

6. Conclusions and policy implications

Probably no one would contest the idea that it is, in principle, more cost-efficient to produce solar electricity and renewable hydrogen in North Africa than it would be in Europe, leading to lower levelized costs of electricity and hydrogen. Hence, logically, one would think that it is beneficial for Europe to import renewable electricity and hydrogen from North Africa where solar and wind energy resources are abundant and affordable – rather than producing them domestically in large quantities. Whether such a supposition is really true, however, also needs to be assessed by analyses with an integrated assessment and/or energy system model, which is what we do in this paper. In particular, we ask ourselves the question: what are the energy system implications of an energy partnership between Europe and North Africa, and what are the impacts in terms of the overall and regional energy system costs? In our previous work [17], we showed that a cross-Mediterranean energy partnership for renewable electricity and hydrogen is indeed cost-optimal, and we extensively described how, consequently, the energy systems of both Europe and North Africa may develop differently from a scenario in which no such partnership materializes. Yet in that paper we also came to the conclusion that the global optimum is associated with a net price to be paid by Europe for such a partnership. This finding came quite unexpectedly. The reason that for Europe an 'efficient' scenario in which an energy trade partnership is realized, is more costly than an 'autarkic' scenario, is the price paid to North African countries for the costly trade of renewable electricity and hydrogen.

In the present paper we introduced a new concept, autarky penalty, which is the price paid for restricting energy trade with a neighboring country or region. In other words, it is the cost of 'going solo', and is in some sense an expression of Adam Smith's paradigm on the benefits of international trade [51]. One of main conclusions of our previous paper [17] – here formulated in terms of this new notion – was thus that the regional AP, under central economic and technological parameter assumptions, may well be negative for Europe (hence, it would gain from going autarkic) even while both the global AP and regional AP for North Africa are positive. In the present study, we demonstrate that if domestic hydrogen production possibilities from solar and wind energy are constrained – for example as a result of space restrictions or limitations emanating from limited public acceptance – Europe's autarky penalty is positive and may increase to 30 billion \$/yr by 2050. In this article we thus numerically corroborate the idea that, when spatial constraints are taken into account, importing (green) hydrogen from North Africa to Europe may prove economically sensible, as also pointed out in Ref. [52]. At the same time, our analysis underlines that the economics of hydrogen production and trade are highly complex, as also broadly recognized in other literature (see e.g. Ref. [16]). In order to complement our study, it is thus necessary to also consider other aspects of a possible hydrogen economy as well as other production options or transportation modes, such as a global green hydrogen credit trading framework [53] or liquid hydrogen trade and hydrogen-based synthetic fuels (see e.g. Ref. [54]).

More broadly speaking, in the present research we quantify, presumably in more detail than in any earlier study, the cost trade-offs of establishing import-export links between Europe and North Africa for two quintessential energy carriers needed for the energy transition and climate change control: renewable (solar and wind energy based) electricity and renewable (water electrolysis based) hydrogen. We find that allowing for trade of renewable energy between Europe and North Africa substantially reduces the EU's domestic renewable energy capacity investments needed to implement its Green Deal and Fit for 55 Programme. In addition to creating import-export scenarios for electricity and hydrogen across the Mediterranean and investigating the cost implications of an energy partnership between Europe and North Africa until 2050, we perform extensive sensitivity tests regarding potential technological developments and sectoral shifts, as well as vis-à-vis potential cost, sectoral & technical asymmetries between Europe and North Africa. In 2022, the EC presented the REPowerEU Plan [55], its response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine. The ambition is to end the EU dependence on Russian fossil fuels and tackle the climate crisis through a number of measures, including accelerated energy savings, diversification of energy supplies, and intensified roll-out of renewable energy to replace fossil fuels in homes, industry and power generation. Among the various initiatives is a target of 10 million ton of domestic renewable hydrogen production and 10 million ton of imports by 2030, to replace natural gas, coal and oil in hard-to-decarbonize industrial and transport sub-sectors. Our findings support these goals, and we conclude that the EU should further an energy partnership with countries in North Africa to facilitate imports of renewable hydrogen. How and by how much to balance between domestic production versus imports is what this paper attempts to explore. We recommend that more studies are undertaken to answer remaining questions and investigate the many dimensions thereof through a broad set of multi-disciplinary studies.

Europe is a densely populated continent, and many areas are reserved for industry and tourism, or protected for environmental and biodiversity reasons. Consequently, the EU is already increasingly facing the challenges associated with the vast amounts of land required for its ambitious plans to massively expand the domestic capacity of renewables like solar and wind energy. Further increasing renewable energy generation capacity in Europe for the specific purpose of green hydrogen production would aggravate fulfilling the already daunting needs for space. Time-consuming regulatory processes as well as possible public acceptance issues related to the installation of large electrolysis plants further add to these challenges. One of the central policy recommendations in this paper is for the EU to seriously consider establishing extensive energy trade partnerships with North African countries, particularly for energy carriers like renewable electricity and hydrogen. Indeed, we have shown in this paper that under the EU's sizeable location challenges for renewable hydrogen production equipment the autarky penalty is likely to be high. Obstacles in terms of local political stability in North Africa, availability of a specialised labor force, and societal wealth distribution, should all be critical components in the EU's decision process, under the realization that a pan-Mediterranean energy partnership may actually help in alleviating some of these hindrances. The Africa-EU Energy Partnership [56], as key political platform through which both continents can work together on energy matters, may be well suited to facilitate this process. Initiatives like the AEEP can be instrumental and should be stimulated, specifically in view of possible trade links for renewable electricity and hydrogen between the two continents. The international consequences of the Russian war in Ukraine, and the subsequent reshaping of trade and geopolitical relations in the global energy arena, should provide further motivation for the EU to seriously establish new renewable energy partnerships across the world, notably with nearby North African countries.

Author credits

B.v.d.Z. and F.D.L. designed the scenarios; F.D.L. produced the scenario runs, did the modelling and created the figures; B.v.d.Z. and F.D.L. undertook the analysis; B.v.d.Z. wrote and revised the article; B.v.d.Z. framed the geopolitical context and drew the policy conclusions; B.v.d.Z. and F.D.L. produced the literature review.

Declaration of competing interest

In view of the submission of our research article "Autarky Penalty versus System Cost Effects for Europe of Large-Scale Renewable Energy Imports from North Africa", we hereby declare that there is no conflict of interest in any possible way.

Data availability

Data will be made available on request.

Acknowledgements

F.D.L. and B.v.d.Z. thank the Ministry of Economic Affairs and Climate Policy of the Netherlands for its continued financial support of research on the international dimensions of the energy transition and climate change mitigation, and the energy security dimensions thereof in particular. The views expressed in this paper are exclusively those of the authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2023.101289.

References

[1] J.L.L.C.C. Janssen, M. Weeda, R. Detz, B.C.C. van der Zwaan, Country-specific cost projections for renewable hydrogen production through off-grid electricity systems, Appl. Energy 309 (2022) 118398.
[2] IRENA, Hydrogen: A Renewable Energy Perspective, International Renewable Energy Agency, 2019.
[3] IRENA, Decarbonising End-Use Sectors: Practical Insights on Green Hydrogen, International Renewable Energy Agency, 2021. May 2021.
[4] IRENA, Green Hydrogen Supply: A Guide to Policy Making, International Renewable Energy Agency, 2021. May 2021.
[5] IRENA, Geopolitics of the Energy Transformation: the Hydrogen Factor, International Renewable Energy Agency, 2022. January 2022.
[6] IRENA, Green Hydrogen for Industry: A Guide to Policy Making, International Renewable Energy Agency, 2022. March 2022.
[7] IRENA, Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers, International Renewable Energy Agency, 2022. April 2022.
[8] IRENA, Global hydrogen trade to meet the 1. 5°C Climate Goal: Green Hydrogen Cost and Potential, International Renewable Energy Agency, 2022. May 2022.
[9] IRENA, Innovation Trends in Electrolysers for Hydrogen Production, International Renewable Energy Agency, 2022. May 2022.
[10] IRENA, Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Trade Outlook for 2050 and Way Forward, International Renewable Energy Agency, 2022. July 2022.
[11] IRENA, The Renewable Energy Transition in Africa, International Renewable Energy Agency, 2021. March 2021.
[12] IRENA, Towards a Prosperous and Sustainable Africa, International Renewable Energy Agency, 2022. February 2022.
[13] B.C.C. van der Zwaan, T. Kober, F. Dalla Longa, A.J. van der Laan, G.J. Kramer, An integrated assessment of pathways for low-carbon development in Africa, Energy Pol. 117 (2018) 387–395.
[14] S.A. Ikonnikova, B.R. Scanlon, S.A. Berdysheva, A global energy system perspective on hydrogen Trade: a framework for the market color and the size analysis, Appl. Energy 330 (2023) 120267.
[15] D. Franzmann, H. Heinrichs, F. Lippkau, T. Addanki, C. Winkler, P. Buchenberg, T. Hamacher, M. Blesl, J. Linßen, D. Stolten, Green hydrogen cost-potentials for global trade, Int. J. Hydrogen Energy 48 (85) (2023) 33062–33076.
[16] V.P. Müller, W. Eichhammer, Economic complexity of green hydrogen production technologies - a trade data-based analysis of country-specific industrial preconditions, Renew. Sustain. Energy Rev. 182 (2023) 113304.
[17] B.C.C. van der Zwaan, S. Lamboo, F. Dalla Longa, Timmermans' dream: an electricity and hydrogen partnership between Europe and North Africa, Energy Pol. 159 (2021) 112613.
[18] IAMC, Integrated Assessment Modeling Consortium, Created in 2007 in Response to a Call from the IPCC, 2020 see, www.globalchange.umd.edu/iamc/home.
[19] H. Müller-Steinhagen, F. Trieb, Sustainable Electricity and Water for Europe, Middle East and North Africa; the DESERTEC Concept for Energy, Water and Climate Security, Presentation of the White Paper Organized by TREC and the Club

of Rome, EU Parliament, Brussels, Belgium, 2007, 10.1615/ICHMT.2009. CONV.100.
[20] F. Trieb, C. Schillings, T. Pregger, M. O'Sullivan, Solar electricity imports from the Middle East and North Africa to Europe, Energy Pol. 42 (2012) 341–353.
[21] Fraunhofer, Supergrid: Approach for the Integration of Renewable Energy in Europe and North Africa, 2016. https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies.
[22] F. Timmermans, "Hearing of Frans Timmermans, Executive Vice-President-Designate of the European Commission (European Green Deal)", Committee on the Environment, Public Health and Food Safety, EC, 2019, 8 October 2019, Brussels.
[23] Energinet Enagás, Fluxys Belgium, GRTgaz Gasunie, Net, O.G.E. Gas, Snam Ontras, Teréga Swedegas, European hydrogen backbone: How a dedicated hydrogen infrastructure can be created (2020). https://www.gasunie.nl/en/news/gas-infrastructure-companies-present-a-european-hydrogen-backbone-plan/$5741/$5742.
[24] Ec, A Hydrogen Strategy for a Climate-Neutral Europe, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 2020. COM(2020) 301 final, European Commission,, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.
[25] EC, Fit for 55: the EU's Plan for a Green Transition, 2020. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.
[26] Timmerberg, Kaltschmitt, Hydrogen from renewables: supply from North Africa to central Europe as blend in existing pipelines – potentials and costs, Appl. Energy 237 (2019) 795–809, https://doi.org/10.1016/j.apenergy.2019.01.030.
[27] A. van Wijk, F. Wouters, in: M.P.C. Weijnen, Z. Lukszo (Eds.), Hydrogen: the Bridge between Africa and Europe", to Be Published in *"Shaping an Inclusive Energy Transition"*, Springer, 2019, 2020, http://profadvanwijk.com/wp-content/uploads/2019/09/Hydrogen-the-bridge-between-Africa-and-Europe-5-9-2019.pdf.
[28] Entsog, Ten Year Network Development Plan (TYNDP) 2018: Infrastructure Report, 2018. https://www.entsog.eu/sites/default/files/2019-06/entsog_tyndp_2018_IN_190523_web.pdf.
[29] Eurostat. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_ti_gas&lang=en, 2020. (Accessed 12 February 2020). Eurostat database: Imports and exports of natural gas by partner country [nrg_ti_gas] and [nrg_te_gas], last accessed.
[30] ECFR, European Council on Foreign Relations, Pipelines and Pipedreams; How the EU Can Support a Regional Gas Hub in the Eastern Mediterranean, 2017. https://www.ecfr.eu/page/-/ECFR211_-_PIPELINES_AND_PIPEDREAMS.pdf.
[31] Entso-e, Statistical factsheet 2018 (2018). https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/Statistics/Factsheet/entsoe_sfs2018_web.pdf.
[32] EC, European Commission, "Electricity interconnections with neighbouring countries. Second report of the Commission Expert Group on electricity interconnection targets", Brussels (2019).
[33] Entso-e, Ten year network development plan (TYNDP) 2018 project database, projects (2018), 29, 283 and 284, last accessed on 11 February 2020, https://tyndp.entsoe.eu/tyndp2018/projects/.
[34] Benasla, Allaoui Hess, Brahami, Denaï, The transition towards a sustainable energy system in Europe: what role can North Africa's solar resources play? Energy Strategy Rev. 24 (2019) 1–13.
[35] Kost Boie, Agsten Bohn, Snigovyi Bretschneider, Ragwitz Pudlik, Westermann Schlegl, Opportunities and challenges of high renewable energy deployment and electricity exchange for North Africa and Europe – scenarios for power sector and transmission infrastructure in 2030 and 2050, Renew. Energy 87 (1) (2016) 130–144.
[36] Navigant, Gas for Climate: the Optimal Role for Gas in a Net-Zero Emissions Energy System, 2019. https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf.
[37] DESERTEC, "Sustainable Wealth for Every Human on Earth", 2021 see desertec.org, last consulted 3 June 2121.
[38] IPCC, Intergovernmental panel on climate change. Special report. Global Warming of 1.5°C, Summary for Policymakers, 2018. Downloadable from, www.ipcc.ch.
[39] IPCC, Climate Change Mitigation, Sixth Assessment Report (AR6), Working Group III, Intergovernmental Panel on Climate Change, Cambridge University Press, 2022.
[40] COP-21, Paris agreement, in: United Nations Framework Convention on Climate Change, Conference of the Parties, vol. 21, France, Paris, 2015.
[41] R. Loulou, ETSAP-TIAM: the TIMES integrated assessment model, Part II: mathematical formulation, Comput. Manag. Sci. 5 (1–2) (2008) 41–66.
[42] R. Loulou, M. Labriet, ETSAP-TIAM: the TIMES integrated assessment model, Part I: model structure, Comput. Manag. Sci. 5 (1–2) (2008) 7–40.
[43] S. Syri, A. Lehtilä, T. Ekholm, I. Savolainen, H. Holttinen, E. Peltola, Global energy and emissions scenarios for effective climate change mitigation – deterministic and stochastic scenarios with the TIAM model, Int. J. Greenh. Gas Control 2 (2) (2008) 274–285.
[44] H. Rösler, B.C.C. van der Zwaan, I.J. Keppo, J.J.C. Bruggink, Electricity versus hydrogen for passenger cars under stringent climate change control, Sustain. Energy Technol. Assessments 5 (2014) 106–118.
[45] T. Kober, J. Falzon, B. van der Zwaan, K. Calvin, A. Kanudia, A. Kitous, M. Labriet, A multi-model study of energy supply investments in Latin America under climate control policy energy economics, Energy Econ. 56 (2016) 543–551.
[46] F. Dalla Longa, L.P. Nogueira, J. Limberger, J.-D. van Wees, B.C.C. van der Zwaan, Scenarios for geothermal energy deployment in Europe, Energy 206 (2020) 118060.
[47] F. Dalla Longa, B. van der Zwaan, Do Kenya's climate change mitigation ambitions necessitate large-scale renewable energy deployment? Renew. Energy 113 (2017) 1559–1568.
[48] TRANSRISK, "Transitions Pathways and Risk Analysis for Climate Change Mitigation and Adaptation Strategies", H2020 Project, 2018. European Commission, Brussels, see, http://transrisk-project.eu/.
[49] EC, European Commission, Green Deal, Brussels (2019). https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.
[50] K. Smekens, G. Martinus, B.C.C. van der Zwaan, in: V. Bosetti, R. Gerlagh, S. P. Schleicher (Eds.), "Market Allocation Model (MARKAL) at ECN", Chapter 9 in Modelling Sustainable Development, Edward Elgar, Cheltenham UK, 2009, pp. 147–156.
[51] Smith, A, 1776, "An Inquiry into the Nature and Causes of the Wealth of Nations".
[52] A. van Wijk, E. van der Roest, J. Boere, "Green Energy for All", 2023 see, https://profadvanwijk.com.
[53] Z.Y. Dong, J. Yang, L. Yu, R. Daiyan, R. Amal, A green hydrogen credit framework for international green hydrogen trading towards a carbon neutral future, Int. J. Hydrogen Energy 47 (2) (2022) 728–734.
[54] P.S.-L. Chen, H. Fan, H. Enshaei, W. Zhang, W. Shi, N. Abdussamie, T. Miwa, Z. Qu, Z. Yang, A review on ports' readiness to facilitate international hydrogen trade, Int. J. Hydrogen Energy 48 (46) (2023) 17351–17369.
[55] RepowerEU, REPowerEU: A Plan to Rapidly Reduce Dependence on Russian Fossil Fuels and Fast Forward the Green Transition, Brussels, 2022, 18 May 2022, see: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131.
[56] AEEP, Africa-EU Energy Partnership, 2007 see: https://africa-eu-energy-partnership.org/.