Large scale renewable energy deployment - Insights offered by long-term energy models from selected case studies

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Abstract

The United Nations’ Sustainable Development Goal 7 (SDG7) of Agenda 2030 calls for an increase in the use of renewable energy sources, among other targets. The percentage of fossil fuel-fired thermal generation for electricity is increasingly being reduced as renewable energy technologies (RET) advance in cost-competitiveness, and as greenhouse gas and industrial air pollutant emission limits become more stringent. In certain cases, renewable energy contributes to energy security by improving a nation’s trade balance, since local resources are harnessed and imports are reduced. RET investments are becoming more frequent gaining a sizeable share in the electric power mix of numerous countries.

However, RET is affected by existing fossil fuel-fired electricity generation, especially in countries that have domestic reserves. While coal may be dirty, others such as natural gas provide multiple benefits, presenting a challenge to renewables. Additionally, RET endowment varies for each geographical location. This often does not correspond to the location of major electricity demand centers. Therefore, large scale RET adoption and integration becomeslogistically more cumbersome, as it necessitates existence of a developed grid network.

Utilizing a series of analyses in two different settings – Africa and Cyprus – this thesis draws insights on RET growth policy and the level of technology representation in long term energy models. In order to capture specific challenges of RET integration, enhancements in traditional long-term energy system models are called for and carried out.

The case of Africa is used to assess adoption of RET under various trade scenarios. It is home to some of the world’s greatest RET resource potential and the single largest potential RET project, Grand Inga. While, the island of Cyprus has goals of introducing large percentages of RET into its electric power mix. Each have important idiosyncrasies which are reflected in the analysis. On the one hand, natural gas competes with RET in Cyprus and forms a key transition fuel away from oil. On the other hand, lack of cross-border interconnectors limit RET project development across Africa.

**Keywords:** renewable energy integration; long-term energy models; gas reserves; policy insights; cost optimization; electricity trade.
Sammanfattning

FN:s globala utvecklingsmål 7 ("Hållbar energi för alla") för Agenda 2030 innefattar bland annat ökad användning av förnyelsebara energikällor. Den procentuella andelen som använder fossila bränslen i elkraftverk sjunker stadigt då förnyelsebara energikällor blir mer kostnadseffektiva, samtidigt som utsläppen av koldioxid och luftföroreningar blir allt mer stringenta. Förnyelsebara energikällor ökar många länder är energisäkerhet då de utvinns lokalt och därmed minskar importberoende. Vidare är investeringar inom förnyelsebara energikällor allt mer utbrett och i flera länder så står dem för en betydande del av energiförsörjningen i landet.

Däremot så påverkas fortfarande andelen av förnyelsebara energikällor av befintliga fossilt drivna elkraftverk där det även finns stora fossilbränslereserver. Utav dem fossila bränslen som används är kol ett ganska smutsig alternativ medans naturgas kan bidra med många fördelar. I tillägg till det så varierar den förnyelsebara potentialen med olika geografiska platser. Dessa platser sammanfaller inte alltid där behoven av elektricitet finns vilket vidare skapar komplexitet i elsystemet då expansion av elnätet behövs till platser där exempelvis sol-, vind- eller vattenkraft finns. Utmaningen i att utveckla andelen förnyelsebart är väsentlig, speciellt i stora komplexa elsystem.

Genom en serie av analyser, vilka tar sin utgångspunkt i fallstudier från Afrika och Cypern, ger denna avhandling insikter om olika policyer för förnyelsebar el samt om vilka teknologier som representeras i långtidsenergimodeller. För att fånga specifika utmaningar med förnyelsebara energikällor har vidareutveckling av långtidsenergimodellerna genomförts.

I fallstudierna för Afrika undersöks förnyelsebara energikällors penetration genom olika scenarion av ökad handel mellan länderna. Afrika är en av de kontinenter som har störst förnyelsebar potential i världen och här finns även världens största förnyelsebara projekt, Grand Inga. I fallstudierna för Cypern analyseras planer på att integrera större andel förnyelsebara energikällor i elproduktionen. Båda Afrika och Cypern har sina egna karaktärsdrag vilka avspeglas i analysen. Cypern har stora oexploaterade gasreserver som konkurrera med förnyelsebara energikällor men samtidigt möjliggör en övergång bort från olja. Å andra sidan i Afrika
saknas elnät som sammanlänkar de olika länderna vilket hämmar utvecklingen av förnyelsebar el.

**Nyckelord:** Förnyelsebarenergi integration; långtidsenergimodell; gasreserver; policyinsikter; kostnader; optimering; elhandel.
Acknowledgements

Deliberately, I chose to write this section of the thesis last. It symbolizes the end of a long journey; a bumpy but definitely rewarding journey. It all started in February 2012 when I pitched a very preliminary MSc thesis idea to Prof. Mark Howells; since then he has been more than a supervisor. During these five years he was available whenever things got difficult. The end result would be one of lesser quality without his support, guidance and motivation. His help will always be appreciated. Remaining on the supervisory front, I would like to thank my co-supervisor, Prof. Holger Rogner, for his willingness to assist throughout this process. He was always eager to share his knowledge and provide constructive criticism.

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List of appended papers

This thesis is based on the following scientific papers:

**Paper I**


**Paper II**


**Paper III**


**Paper IV**

**C. Taliotis**, A. Shivakumar, V. Sridharan, M. Howells, “Regional effects of Grand Inga: A project-focus application of TEMBA (The Electricity Model Base for Africa),” [Forthcoming]. Submitted to *Energy for Sustainable Development*.

**Paper V**


**Paper VI**

Paper VII


Additional publications

Other publications that the author has contributed to include:


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1 Introduction

This chapter of the dissertation begins with background information on the need for quantitative analysis of energy systems when assessing acceleration of renewable energy technology investments. The role of long-term energy models in the provision of policy insights is then discussed. The second part of the chapter defines the scope and aim of the thesis. The chapter continues with a brief explanation on the disposition of the dissertation. The state of the art is presented in the final section, where gaps in literature are identified.

1.1 Background

Energy is fundamentally interwoven with the global economy. It is essential, as it forms an input to nearly all goods and services [1]. Similarly, access to affordable, uninterruptible supply of modern energy services is key to local socio-economic development [2]. The lack of adequate electricity supply infrastructure and the frequent power outages in certain parts of the world, such as Sub-Saharan Africa, is recognized as a significant obstacle for economic growth [3]–[5]. At the same time, universal access to affordable, reliable and sustainable modern energy is one of the United Nations Sustainable Development Goals (SDG7) [6]. To achieve this goal, an increase in the provision of modern energy forms, such as electricity, needs to occur, and hence investments to supply this are required [7]. The specific sub-targets of SDG7 as formulated by the UN aim by 2030 at (a) achieving universal access to affordable, reliable and modern energy services; (b) increasing the share of renewable energy in the global energy mix, and (c) doubling the energy efficiency improvement rate globally [8]. Even though there is no order of priority for the UN SDGs, SDG7 is an enabler for the achievement of other SDGs. For instance, lighting is essential in reading at night, which relates to SDG4-Quality Education, while electricity facilitates in pumping and purifying water, which relates to SDG6-Clean water and sanitation.
The Paris Agreement at the recent COP21 further reinforces the imminent transition towards a low carbon economy [9]. Representatives from 195 nations agreed on a long-term goal to keep the global average temperature increase well below 2°C, highlighting the necessity to peak global greenhouse gas emissions as soon as possible. In light of the outcomes at COP21 [9], it is apparent that a transformation in the current global energy system is called for. The lock-in effect of past fossil-fuel infrastructure choices made by industrialized nations has contributed to the escalation of greenhouse gas emissions [10]. Alternative clean technologies will have to be promoted to reduce the emissions in many developed areas. This promotion may be expensive since existing infrastructure must be upgraded or replaced; low demand growth rates only exacerbate the transformation. In contrast, developing countries are expected to grow at a rapid pace. They can take advantage of their latecomer effect and invest in green energy solutions directly [4].

Most sectors of the energy system in a majority of countries remain largely reliant on the use of conventional fossil technologies. These can be inefficient and highly polluting. In terms of fuel diversity in electricity supply, developing areas of the world have relied heavily on fossil fuel-fired generation. However, there can be diversity depending on the local resource base. Hydro and cane residues, play an important role in Brazil, for example [11]. While in sectors such as transport, fuel diversity is exceptionally low across the globe [12], as it is dominated by oil products.

In terms of electricity supply, low-carbon technologies include nuclear and fossil-fired plants with carbon capture and storage. The former has a varying degree of public acceptance internationally [13], while the latter option has not yet reached commercialization [14]. As such, renewable energy technologies will play an important role in the sought reduction of greenhouse gas emissions.

A shift towards renewable energy is already observed and is expected to continue; at least in electricity generation. Investments in new renewables amounted to 191 billion USD in 2010 as compared to 2 billion USD\(^1\) in 1990

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1 Both figures refer to USD 2005 values.
According to the IEA’s New Policies Scenario, a third of the world’s electricity generation will be based on renewables by 2040, while as compared to 2013 global installed capacity of wind and solar PV is expected to increase by 300% and 500% respectively [16]. However, reaching decisions for energy infrastructure investments that are sustainable and cost-efficient, without compromising energy security, is not a trivial task. This is in part because while, low carbon, many renewable power generation technologies produce variable levels of power generation. They may require massive deployment of supporting infrastructure. Or, countries may be endowed with valuable fossil reserves that provide opportunity for economic gains.

As the share of intermittent renewable energy increases in electricity supply, complications in terms of system reliability may be introduced in the respective system; this has been widely acknowledged in existing literature [18]–[20]. The inherent intermittency of, for instance, solar and wind technologies introduces challenges, as they substitute conventional thermal technologies that are often dispatchable. To an extent this can be tackled with improved forecasting [21]–[23]. Nonetheless, unexpected rapid fluctuations in generation can lead to power outages if there is inadequate flexibility in the operation of the grid. System reliability concerns become increasingly significant if one takes into account an isolated system as is the case of Cyprus [21]. Dispersion of renewable energy technologies (RET) over large geographic areas can reduce this risk [24], while the use of grid interconnectors can further facilitate in this

2 Energy security is affected by the following three aspects [17]:

a) Robustness, relating to threats that can to a large extent be expected and thus addressed with. These include availability of reserves and capacity additions to meet future energy demand.

b) Sovereignty, which is primarily affected by external factors, such as geopolitical tensions, acts of terrorism, physical disruptions in supply and fuel price fluctuations.

c) Resilience, relating to threats that cannot be predicted, such as extreme weather events and market volatility. This has an immediate connection with the design of the system in question and its degree of flexibility.
regard, as it enables access to power infrastructure of neighboring systems [25]. Additionally, improvements in the flexibility of systems with high variable renewable energy share can be achieved through the deployment of storage options, demand-side technologies, fast-response conventional power plants and dispatchable renewable generation options [24], [26].

Investments in RET generation options need equivalent investments in transmission and distribution infrastructure. This is especially the case since demand and supply are typically in different areas. Certain regions such as Africa have immense RET potential [27] but an underdeveloped state of generation and transmission infrastructure. Another key barrier in unlocking RET potential in Africa is the limited network of interconnectors and associated low trade levels [28].

Future deployment of RET has to be assessed in the context of the entire generation mix. Fossil fuels currently claim a significant share of this [16]. As CO₂ emission reductions are pursued due to COP21, since gas has a low carbon-intensity [29], it may play an important role in generation, compared to more carbon intensive fossil fuels. However, not all countries have domestic gas reserves and thus rely on imports, which affects energy security. This is especially the case for the European Union (EU), which aims to reduce its dependence on Russian gas [30]. Any potential domestic EU gas reserves are thus important.

Arguably, energy models are useful in decision making in relation to renewable energy adoption and integration. The research field of energy modelling flourished out of the necessity to understand the unsecure environment created by the 1973 oil embargo [31]. Energy models can be characterized as simplified representations of reality, comprised of mathematical equations, with the goal of comprehending complex interactions in a given energy system and providing policy insights [31]. In

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3 This, however, might prove to be a false panacea. In an interconnected system, if electricity is cheaper across the border, it may be cheaper to import electricity and reduce the use of domestic generation sources. Similarly, in regards to system reliability, generation fluxes can occur at both sides of the border simultaneously, thus risk may not necessarily be mitigated.

4 Natural gas has about 51-57% the CO₂ intensity of coal and 71% the equivalent of crude oil [29]. It has thus often been viewed as an important transition fuel.
terms of assessed timeframe, short-term models analyze systems over periods of seconds to days, mid-term models focus over days to years, while long-term models typically investigate energy system behavior over decades [32]. Due to their low temporal resolution, long-term energy models often do not address grid stability issues. The value of incorporating these aspects into long-term energy analyses has been demonstrated and implemented by Welsch et al. [33].

Energy system models can generally be categorized into bottom-up technoeconomic models and top-down macroeconomic models. The former employ a high degree of detail in terms of technologies but cannot provide any insights on net impacts across the economy. The latter look into aggregated sector-specific energy demand and supply and assess effects on the entire economy but are not suitable for analyzing potential technology deployment, due to insufficient detail in this regard [34], [35]. Numerous hybrid models have been developed [36]–[42] in an attempt to use the strengths and limit the weaknesses of the two categories.

Optimization models form a subcategory of energy system models, whose purpose is to fulfill a specific objective function. Frequently, their aim is to minimize a particular system’s cost. Optimization models can represent large integrated, multi-resource systems. In practice, focus is usually on a single sector, such as electricity supply, thus optimization takes into account only a fraction of the economy, ensuring that demand and supply are in equilibrium [32]. Such models are also referred to as partial-equilibrium models. It is apparent that different energy models have their strengths and limitations, which define their most suitable areas for application.

In terms of spatial focus, assessments vary considerably. Energy models have been used to analyze system pathways on a global [43]–[45], regional [46]–[49] national [50], [51], or even village scale [52], [53], while focus on a single sector is also frequent [54]–[56]. National models are typically more detailed than global and regional models, but tend to rely on assumptions in regards to exogenous trade\(^5\). Less geographic detail implies

\(^5\) An example would be that of electricity trade between two countries; A and B. In a cost optimization, if the model developed defines in detail only the system of country A, assumptions would be necessary as to the price at which electricity can be imported.
a decrease in the required model development and calculation time. On the other hand, with regional aggregation physical limitations, such as transmission line capacity between countries, are masked. Also, the use of average data over a collection of countries, such as national emission limits, can misrepresent important unique characteristics of a system and its constraints [35].

The degree of appropriate model complexity\textsuperscript{6} is a topic that is of concern across various disciplines making use of mathematical models to support decision-making. This observation includes but is not limited to climate system models, earth science models and combat models [58]–[62]. There is a general consensus in literature from these disciplines that increased complexity does not necessarily lead to improved insights. A high degree of complexity implies longer model development timeframes and can add uncertainty or introduce obstacles in fully comprehending the system dynamics and model results. On the other hand, limited detail in a model can lead to an inept representation of the system. Its outputs may therefore skew insights and their ‘real-world’ value [59], [63]. Arguably, these observations apply also in the case of energy systems models. However, it is believed that added complexity in energy systems modelling is necessary to comprehend obstacles faced by RET adoption and integration policy. RET intermittency, lack of supporting grid infrastructure and competition with other energy carriers limit the rate of RET deployment. Insights on the topic of model detail are offered as part of this thesis.

1.2 Scope and aim

The primary aim of this dissertation is to provide targeted insights on renewable energy technology growth policy - drawing on long term energy model development. Selected aspects of SDG7 are addressed by this thesis; specifically, those of increased access to electricity and increased shares of

\textsuperscript{6} The term complexity is defined as “the state of having many different parts connected or related to each other in a complicated way” [57] and is used here to refer to the degree of detail that is included in a model.
renewable energy. However, with growing shares of RET in the generation mix, potential benefits and challenges should be adequately represented in energy system models. Conclusions are drawn on different levels of detail in terms of technology representation in these models with an emphasis on non-renewable technology representation. Advancements in the modelling representation of selected relevant case studies, as compared to what is available in existing literature, are carried out. A focus is given on the electricity supply sector of the case studies to assess the array of insights that are offered in each case. In order to fulfill the aim of the thesis, the following three sets of research questions have been identified:

- **Research question A:** Is the long term transition to increased RET adoption and integration straightforward?
- **Research question B:** What insights do we get when we move between case studies? One size does not fit all, yet we use the same modelling framework. Are there new situation specific insights gained?
- **Research question C:** What might be some key, perhaps general, measures necessary to achieve the technology deployment levels foreseen in each case study?

### 1.3 Disposition

The thesis consists of a cover essay, which summarizes and brings together the key research outputs. The papers on which it is based on are included as separate appendices.

#### 1.3.1 Cover essay

A variety of real-world cases in which increased renewable energy adoption and integration are key aspects are considered in the dissertation. The first case focuses on the electricity supply system of a continent; that of Africa. The second case zooms in on a single colossal renewable energy project – the Grand Inga in the Democratic Republic of Congo. This project was selected as it would allow valuable insights when examined as a separate case.

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7 One overarching example is the deployment of renewables in a large interconnected system, such as Africa, versus an isolated national grid (i.e. Cyprus).
part from the first case. The third and final case study concerns the electricity supply system of Cyprus; an island both geographically and in terms of grid interconnections, but with large unexploited domestic gas reserves.

The different focus and geographic setting of the studies provides diversity which is reconciled in the cover essay. Despite contextual differences, a common conceptual framework and approach is followed throughout. The papers include information that is occasionally repeated in the body of the thesis (or between them), as basic background information is deemed necessary for readers of individual papers.

The first chapter of the dissertation provides background information on the necessity for comprehending energy systems and the utility of energy system models in energy planning. The scope and research aim is then defined. The second chapter presents the methodology followed during the entire thesis duration. Chapter 3 presents the key findings from the assessed case studies and provides an interpretation of the analysis. The final chapter of concludes by discussing the contribution of the thesis, recognizing its limitations and identifying areas for future research.

1.3.2 Appended papers

Seven individual peer-reviewed research papers comprise the basis of the dissertation. Five of the papers have been published in refereed journals, while two of the papers are pending peer review decision.

Paper I


Author’s contribution to the paper: Refinement of model structure. Update of key input assumptions (technology cost and performance characteristics, demand projections, fuel prices, solar PV and CSP generation profile). Development of scenarios, running the model, extracting, plotting and analyzing model results, drawing conclusions, along with substantial paper write-up. The other authors provided initial model setup, values for RET potentials by country, supervision and guidance throughout the analysis.
Paper II


Author’s contribution to the paper: Refinement of model structure. Update of key input assumptions (technology deployment rates, grid interconnector availability and costs). Development of scenarios, running the model, plotting and analyzing model results, drawing conclusions along with substantial paper write-up. The other authors provided initial model setup, assisted with data gathering regarding hydropower projects, results extraction and the development of some of the figures, supervision and guidance throughout the analysis.

Paper III


Author’s contribution to the paper: Model structure and assumptions largely based on Paper I. The author carried out the development of scenarios, running the model, extracting, plotting and analyzing model results, drawing conclusions, along with substantial paper write-up. The rest of the authoring team provided editorial revisions, supervision and guidance throughout the analysis.

Paper IV

C. Taliotis, A. Shivakumar, V. Sridharan and M. Howells, “Regional effects of Grand Inga: A project-focus application of TEMBA (The Electricity Model Base for Africa),” [Forthcoming]. Submitted to Energy for Sustainable Development.

Author’s contribution to the paper: Model structure and assumptions largely based on Paper II. The author carried out the development of scenarios, running the model, extracting, plotting and analyzing model results, drawing conclusions, along with paper write-up. The rest of the authoring team provided some updates on key input data, along with supervision and guidance throughout the analysis.
Paper V


**Author’s contribution to the paper:** Development of model structure, gathering and transforming input data. Development of scenarios, running the model, extracting, plotting and analyzing model results, drawing conclusions, along with substantial paper write-up. The rest of the authoring team provided editorial revisions, supervision and guidance throughout the analysis.

Paper VI


**Author’s contribution to the paper:** Development of model structure, gathering and transforming input data. Development of scenarios, running the model, extracting, plotting and analyzing model results, drawing conclusions, along with substantial paper write-up. The rest of the authoring team provided editorial revisions, supervision and guidance throughout the analysis.

Paper VII


**Author’s contribution to the paper:** Development of model structure, gathering and transforming input data. Development of scenarios, running the model, extracting, plotting and analyzing model results, drawing conclusions, along with substantial paper write-up. The other authors provided editorial revisions, supervision and guidance throughout the analysis.

A consolidated contribution to knowledge made by the author is included in the concluding section of the thesis.
1.4 Status of literature and identified gaps

1.4.1 Africa

Taking into consideration that SDG7 of the United Nations aims to “ensure access to affordable, reliable, sustainable and modern energy for all” [6], it can be argued that regions with the least access to such services should be targeted first. Sub-Saharan Africa is lacking in this regard, as approximately 620 of the total 940 million inhabitants have no access to electricity in the region [64]. Yet in terms of a coherent investment outlook for the power sector, the African continent is incredibly understudied as compared to its needs for infrastructure development. The focus of this work however, is on supply. This is consistent with SDG7’s second target: By 2030, increase substantially the share of renewable energy in the global energy mix. Africa, in particular, is home to some of the most ambitious plans for RET expansion – and home to much of its economic untapped potential [27]. These include Desertec in the North [65], the Grand Renaissance Dam in Ethiopia [66], the Grand Inga project [67] and others.

An initial attempt at identifying the continent’s optimal technology mix has been carried out by the Programme for Infrastructure Development in Africa (PIDA) [68], where an optimization model was employed to investigate three different scenarios of integration, and hence electricity trade, between regions of the continent for up to 2040. A subsequent study also used an optimization model to assess the financial impact of increased electricity access and regional integration in 43 Sub-Saharan African countries for the period 2005-2015 [69]. However, even though the renewable energy potential is recognized in the former study, both of these underplay the role to be played by RET in increasing electricity access across the continent. To an extent this can be explained by the significantly higher investment cost for RET assumed in literature at the time and by the fact that the latter study does not consider biomass-fired, wind and solar CSP generation options; perhaps due to the model horizon ending in 2015.

Expansion plan studies have also been carried out with focus on single power pools of Africa (specifically East [70], West [71] and Southern [49], [72], [73] African power pools). An optimization approach has been used in another study to investigate country-by-country generation and transmission of renewably generated electricity. Optimization in this study
was performed in 5-year time-steps for the period 2010-2025 and only considered centralized generation options [74]. If scheduling dynamics of shorter, say annual time-steps are important they would be missed. A long-term optimization model coupled with a short-term power systems model was used by McKinsey&Company in their analysis of the Sub-Saharan electricity sector [75]; optimization was only performed for 2020, 2030 and 2040. Representation of transmission in this case is done in a simplistic manner, as transmission and distribution are assumed to follow a fixed relation to generation investments. Similarly, KPMG has published a Sub-Saharan African power outlook based on what appears to be a similar analysis [28]8. Further, the latter two examples neither appear in the peer-reviewed literature, nor offer enough information on input data and assumptions for the modelling experiment to be repeated. Thus, at the time of writing, no reviewed academic contribution reports a modelling effort that assesses the annual electricity transmission, supply, centralized and decentralized, of each country on the entire continent in the long-term.

In order to achieve higher electrification rates across Africa, sizable investments in generation infrastructure are necessary. Average annual investments in generation and transmission infrastructure could amount to over 70 billion USD for universal access to electricity in Sub-Saharan Africa [76]. Successful development of large scale projects could provide the push necessary for cascading additions in installed capacity [76]. One such potential project is the Grand Ethiopian Renaissance Dam, around which political tension has built up between Ethiopia and downstream Egypt, despite the fact that literature argues for expected transboundary benefits [66]. A computable general equilibrium (CGE) analysis of the Eastern Nile economies (Egypt, Ethiopia and pre-2011 Sudan) has indicated that, once the dam is operational, positive economic impact is to be expected across the region, as trade of low-cost electricity can boost the neighboring economies [77].

Another well-reported project was the Desertec initiative, which proposed the deployment of up to 600 GW of RET by 2050 in the Middle East and

8 The approach used for the analysis and the structure of the model are not clear in the respective publication.
North Africa, with the goal of exporting inexpensive, low-carbon electricity to Europe [65]. Despite this large addition in generating infrastructure, electricity access rates in sub-Saharan African countries would not have been improved in any direct way. It may be argued that the Eurocentric nature of the project is also reflected by the focus of relevant analyses available in literature [78], [79].

Similar to Desertec, when the concept of the Democratic Republic of Congo's (DRC) Grand Inga project was first developed in the mid-20th century, it was mainly to benefit prospective relocated European heavy industry [80]. The low cost of electricity envisaged to be achieved by the world’s to-be largest hydropower facility\(^9\) is the main driver for the future development of the project. Nonetheless, if the project becomes operational it will have an effect on a number of African economies as it can generate large volumes of cost-competitive electricity.

Existing long-term energy planning studies have taken project development into account (see for instance [49], [74], [82]). However, at the time of writing important gaps exist in the peer-reviewed literature. No account has been made that simultaneously assesses more than one scenario of its development, across all regions, all trade routes and all countries in the continent with annual time-steps. Without this, insights relating to infrastructure scheduling, transmission development and security of supply are not possible.

**Contributions of this work**

In this thesis, Paper II reports the development of a detailed, coherent, long-term, analytical country-by-country, annual investment toolkit for the entire African continent that is open source and accessible by members of the research community. Papers I and II assess the future role of RET in improving electricity access in Africa under scenarios of different levels of cross-border integration.

Paper III assesses the selected techno-economic viability of the Grand Inga project for a range of project development and electricity demand

\(^{9}\) Currently, the biggest hydropower plant is the Three Gorges dam with a capacity of 22 GW, while the Grand Inga, if developed fully, can reach a capacity beyond 40 GW [81].
scenarios and identifies the power pools that will import electricity from Inga. Paper IV takes a more detailed approach and investigates the project’s impact on the generation mix at the national level for selected countries. In the latter, export routes are identified and the competitiveness of proposed cross-border interconnector projects is noted.

Papers I-IV provide insights regarding renewable energy adoption in a large, increasingly interconnected electricity system. The size of the system, both in terms of capacity and geographical coverage, allow for the incorporation of high shares of variable RET. In the context of Africa, capacity additions, be it RET or conventional thermal plants, will be used to satisfy the rising electricity demand. However, established grid systems in developed countries already have sufficient capacity to meet the demand. This creates an inertia that is difficult to change. New RET additions may displace existing generation options.

1.4.2 Cyprus

Further, deployment of intermittent RET may be technically challenging. This becomes a prevailing issue in small isolated grid systems, such as Cyprus. The small European Union member state needs to conform with EU directives regarding renewable energy penetration\textsuperscript{10}.

An initial study that guided the country’s National Renewable Energy Action Plan, had concluded that the cost of electricity would unavoidably increase so as achieve the set targets \cite{84}. However, that was conducted before the sharp decline in photovoltaic investment costs \cite{85} and in a period of high oil price. The study also assumed that a fuel shift away from oil products to natural gas would have occurred, which is not yet the case. Additionally, the study had suggested that wind would contribute the greatest to the renewable energy share. Experience from existing Cypriot installations has shown that the average capacity factor of wind is well below 20\%. While, generation output is largely erratic (Figure 1). Thus, photovoltaics are the technology that is currently increasing its capacity \cite{86}.

\textsuperscript{10} The share of renewable energy in final energy consumption should reach 13\% by 2020. In the electricity sector this corresponds to 16\% \cite{83}.
The case of Cyprus is in some ways comparable to that of Ireland, an island nation that has pursued an increase in renewable energy generation share following a series of studies. A long-term power expansion study was coupled with resource assessment, dispatch, network, and costs and benefits studies to produce a consolidated assessment for the integration of RET in its electricity supply [87]. The literature of grouping some of these aspects, and in particular incorporating short-term system characteristics used in dispatch analyses into long-term energy system models, is not extensive. However, a growing number of examples exist [88]–[90], while Welsch et al. have demonstrated the applicability and usefulness of such a single tool using Ireland as a test case [33]. This approach has not been tested for a smaller and more demanding system, in terms of flexibility requirements, such as Cyprus.

An optimization model, based on the WASP software 11, has previously been employed to examine effects on electricity cost by the EU’s 2020

![Graph showing wind generation output in Cyprus during a week in April, 2016.](image)

**Figure 1 – Wind generation output in Cyprus during a week in April, 2016.** Installed capacity at the time corresponded to 157 MW [91].

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11 The Wien Automatic System Planning Package (WASP) has been developed by the International Atomic Energy Agency and is a cost-optimization tool used for long-term expansion planning in the electricity supply sector. The least-cost solution is provided for a set of input parameters and constraints that define the technical, economic and environmental characteristics of the respective system [92].
renewable energy target [84]. This model focused solely on electricity generation. A model of Cyprus for the entire energy system exists within a regional model, which is used for informing energy policy decisions of the European Union [93]. However, not all of the assumptions used are accessible\(^\text{12}\), which does not allow replication of the analysis.

**Contributions of this work**

Research conducted as part of this thesis aims to improve these areas. In Paper V the potential joint exploitation of natural gas reserves by Cyprus and neighboring Israel is used as a research focus, upon which the electricity supply systems of the two countries are defined and modelled. This provides a preliminary overview of how regional gas may affect the power sector outlook of Cyprus.

Paper VI then increases the level of detail for the Cypriot system in order to assess the cost-optimum share of renewable energy generation up to 2030. The framework provided by Welsch et al. [33] for Ireland is then utilized in Paper VII for Cyprus. While doing so the representation of the system’s technical constraints is improved. This helps to better assess the cost-competitiveness of RET in a long term model under short term constraints. It also allows an examination of RET deployment and its interaction with the broader system. Outputs of this paper are presented in the context of a number of gas-fired generation scenarios.

More detail of each of salient aspect of the case studies is available in the individually appended papers.

\(^{12}\) Examples of important data and assumptions that are not publically accessible relate to: techno-economic parameters of technologies (such as investment cost, efficiency, emission factors), availability of renewable energy sources, country-specific performance of renewable energy technologies, country-specific fossil fuel prices, potential forced investments, decommissioning dates of existing infrastructure etc.
2 Methods

This section summarizes the approach followed from conceptual model development to results interpretation in the dissertation. The specific model structure, input data and key assumptions for each of the case studies are provided in the individually appended papers so repetition will be avoided here.

2.1 Optimization models

Long-term cost optimization models have been used for the quantitative analysis presented throughout this thesis. Papers I, III, V and VI are based on models built in the Model for Energy Supply Systems and their General Environmental impact (MESSAGE) [43], whereas model development and analysis of papers II, IV and VII has been conducted in the Open Source Energy Modelling System (OSeMOSYS) [94]. Both of these models are demand-driven, which means that their objective function is to satisfy an exogenously defined final energy demand at the lowest possible cost. Depending on assumed techno-economic performance characteristics of included technologies, fuel prices, emission limits and other system constraints, the model then identifies a cost-optimal technology mix.

At this point, it is important to recognize selected key caveats associated with these models. Optimization models assume that a perfectly functioning and predictable market exists in the system in question. This in turn implies the following [32]:

a) **Perfect competition** occurs between the market participants, who act as price-takers and provide energy at a marginal production cost.

b) **Perfect foresight** allows market participants to be fully aware of all present and future conditions affecting the cost at which they provide or purchase energy. For instance, since fuel prices are defined exogenously, the model provides a solution taking into account a price forecast for the entire model horizon, which is assumed to be impeccable.

c) **All decisions are ultimately based on cost**, which does not necessarily reflect reality. Consumer behavior varies significantly between individuals, as one may choose to purchase a fuel-intensive sports car for lifestyle reasons, instead of a hybrid electric
car, which in the long-run could potentially result in considerable cost savings. Additionally, it is difficult to assign monetary value on certain aspects, such as energy security risks.

These caveats are kept in mind when drawing conclusions from the outputs of the optimization models used in this dissertation. As highlighted early-on in relevant literature [31], the purpose of energy modelling in this context is not to make predictions on what, for instance, the technology mix will look like in 2050, but rather to provide insights and facilitate in the formulation of robust energy policy decisions based on the objectives and the local specificities of each case. The model simply provides an internally consistent image of an optimal future state.

2.2 Model structure

A common approach is employed in the structural development of the models in all papers. Technologies are connected in energy chains and act as the links between the various energy forms, either bringing energy into the system or converting it into a different form. Technologies at the primary level supply the system with energy, while technologies at the secondary level convert, for example, gas into electricity. Electricity is then transmitted and distributed through the system at the tertiary level and reaches the consumer at the point of demand.

Figure 2 – Reference Energy System example of a simple energy system
Figure 2 illustrates a simplified representation as an example of a fictional electricity supply system. The horizontal lines indicate demands and flows of energy, while the boxes indicate groups of or individual technologies. The level of granularity\textsuperscript{13} adopted in the model varies in each of the outputs. Further information on this along with the specific structure adopted in each case study are available in the appended papers.

### 2.3 The importance of scenarios

All the papers composing this thesis investigate a number of scenarios. While used by individuals and society for millennia, following World War II the formalized use of scenarios in the modern era arose primarily as part of military strategy exercises that aimed at being prepared for different alternatives [95]. The emergence of simulation models and the subsequent evolution of “systems analysis”, eventually led to the adoption of scenario techniques, many of which originate from work carried out by The Rand Corporation in the USA for defense oriented studies [96]. The importance of scenario analysis increases when uncertainty and consequence increases. Just as the use of energy system models rose following the oil embargo in 1973 [31], the practice of scenario planning rapidly grew during the same period [96].

In the same way, there is a great deal of inherent uncertainty when carrying out electricity supply development plans for a given system. When investigating the potential deployment of RET in the generation mix, there is a number of variables that directly affect decision-making. Since a cost-optimization modelling approach is used in this dissertation, some of the recurring key aspects include the following:

i. What technology learning rates\textsuperscript{14} should be assumed for RET? As experienced in recent years, the rapid decline in the cost of solar

\textsuperscript{13}In this thesis the term “granularity” refers to the amount of detail adopted in the model to represent the system in question. In the African case, two different levels of spatial detail are used: power pools and national grid systems. In the case of Cyprus, the final model is one of high temporal and technological complexity.

\textsuperscript{14}Learning rates in the case of energy technologies refers to the reduction in technology production cost as a result of increased levels of technology adoption and associated experience gained by manufacturers [97].
photovoltaics has improved cost-competitiveness of this technology [85], which was to a large extent unexpected. Future learning rates for photovoltaics and other RET though remain uncertain, which means an assumption has to be made.

ii. Which enabling technologies should be taken into consideration? For instance, a grid interconnection with a neighboring country may reduce the risk of supply shortage or the need for curtailment in periods of unexpected shifts in generation from variable RET. Similarly, storage options can be used both for energy arbitrage and provision of ancillary services [98]. However, the future role of energy storage depends on how cost and performance of the various technologies will progress [99].

iii. To what extent can thermal power plants provide flexibility so as to cope with sudden generation shifts from variable RET? What is the potential for demand-response mechanisms in the system in question?

iv. What will be the levelized cost of generating electricity (LCOE) for fossil-fired power plants in the future? This relates to a number of factors, such as the investment cost of the facility in question, projected fossil fuel prices, for which values vary greatly between scenarios even within single pieces of literature [16], potential carbon dioxide emission costs or restrictions on air pollutant emissions.

As such, the assessment of a set of scenarios that are able to encompass the major uncertainties becomes imperative in any such type of analysis. An iterative approach can be adopted, in which the technical, behavioral and financial feasibility of the model outputs can be assessed sequentially in a range of scenarios. If carried out properly, scenario analysis can help in comprehending how the key decision variables interrelate and affect the system in question. At the same time, based on the outputs, the modeler can formulate insights and better understand the implications of specific policy or investment decisions [100]. In this way, robust or poor decisions can be identified for instance, if they appear recurrently in all scenarios or in just one extreme scenario respectively.
2.4 Case study elaboration

As mentioned earlier, different case studies have been used to compile this dissertation; within each are more detailed ‘deep dives’. Two settings are chosen where RET development appears important. One in which a large potential of unexploited renewable energy resides - Africa. Another, where a radical transformation is expected as a country moves from oil-fired to RET generation - Cyprus.

Initially, through the development of a five-region model of Africa, the research focuses on identifying cost-optimal levels for RET deployment on the African continent as a way to increase electricity supply. From this, trade is identified as essential in tapping into unexploited RET potential across the continent. Since trade is identified as such an important factor, the analysis is steered away from the generalized representation of power pools into country level resolution for the continent to look at trade impacts on RET deployment at a higher detail. Subsequently, one mega-project and its implications are examined. The hydropower potential of the Grand Inga project in the Democratic Republic of Congo, which if fully developed will be the single biggest RET project in the world.

The case of Africa, which currently has an underdeveloped power sector is then contrasted with a very different setting; the case of Cyprus. The electricity supply system of Cyprus is well developed and is based on expensive and polluting oil. However, it needs to conform with EU regulations (on the share of renewables in the energy mix and CO₂ emission reductions) and international legislations (on industrial air pollutant emission reductions, such as SOₓ). As RET pollute little and investment costs are dropping, their deployment is likely to be straightforward and have multiple benefits. However, Cyprus is also home to some of Europe’s most strategic untapped gas reserves. Like renewables, gas provides key benefits. While it is a fossil fuel, it is lower carbon-intensive and pollutes less than others. First, an investigation is conducted on the potential role that gas may play in the power system – reporting the impact on RET investment. RET investment is then investigated in detail. Not only the role of gas is considered, but also the variability of new RET investment is accounted for. The following subsections present the main conceptual differences that influence the modelling approach.
2.4.1 Africa – An interconnected grid system

The lack of adequate power infrastructure in Africa has been highlighted in the literature [3], [7]. As population and GDP increase across the continent, final electricity demand is estimated to rise threefold by 2040 as compared to 2012 [64]. The underdeveloped state of electricity supply offers an apparently straightforward opportunity to directly deploy low-carbon generation technologies, thus avoiding the transition currently faced by developed nations. Africa is endowed with immense hydro and non-hydro renewable energy potential [27], [101]. On the other hand, integration of RET in a large scale might not be trivial in terms of technical challenges, capital mobilization and local government planning. In order to achieve SDG7 and maintain a cost-optimum generation mix, regional cooperation will be necessary. Even though the deployment of trade links between countries facilitates incorporation of higher shares of variable RET in the generation mix [25], in the African context experience in the operation of a competitive electricity market for countries within a power pool is limited. Even though power pools have been set in place, minimal trading occurs. Only 7% of the electricity is traded in Western and Southern and 1% in Eastern and Central African Power Pools [28].

Regardless of this obstacle, assuming perfect market conditions, the effect of trade is investigated within this case study to assess the hypothesis of increased electricity exchanges acting as facilitators of higher RET deployment. It should be mentioned that since optimization models assume perfect market conditions, model outputs are presented in terms of potential for improvement so as to recognize the extent at which cost-competitive investments of RET are possible across the continent. The African case study is chosen as there is substantial untapped renewable energy potential. The continental scale allows for different levels of aggregation, which results in the two models of different spatial granularity15.

15 Papers I and II assess the future role of RET in meeting the increasing demand for electricity in Africa, first in a coarse aggregated manner, in five distinct power pools, and later in a more detailed spatial resolution, representing each country separately.
Analysis for this case study provides a comparison of results from a range of scenarios. These scenarios investigate impact on RET deployment by:

a) Different levels of cross-border interconnection across the African continent;
b) Different levels of final electricity demand for the entire African continent (only in the aggregated model);
c) Potential introduction of CO₂ tax in Northern and Southern Africa (only in the aggregated model).

2.4.2 The Grand Inga project – A project specific perspective

In order to promote access to modern energy services, as part of SDG7, a higher access to electricity is necessary across Africa. Using the most cost competitive supplies will be essential, but not sufficient, to help keep electricity cost at affordable levels. The potential of harnessing the Congo River, although identified in the first half of the 20th century, is one such largely untapped renewable energy source [67] that can significantly increase the generating capacity of the continent.

Nonetheless, the project has suffered from exceptionally long delays in the past and its full development is not at all certain. The inherent necessity for capital investments for the project itself, as well as for the grid interconnectors that will bring the generated electricity to points of demand, are two major obstacles. To an extent capital might be secured through bilateral power purchase agreements [102]. Nevertheless, to allow for full project development, investors need to be convinced of the project’s techno-economic viability in a range of scenarios, while areas in Africa where Inga’s electricity will be demanded have to be identified.¹⁶

The Grand Inga project is an ideal case of a renewable energy mega project that can facilitate the achievement of SDG7, and its second target¹⁷, in particular. The case study can indicate that cost-competitive electricity

¹⁶ The former is the main objective of Paper III, while the latter, along with the identification of likely trade routes, is the aim of Paper IV. The models used in Papers I and II and form the basis for analysis in Papers III and IV respectively.

¹⁷ By 2030, increase substantially the share of renewable energy in the global energy mix

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may have cross-border benefits and it promotes the concept of regional cooperation, which is key in exploiting the continent’s abundant natural renewable energy sources. Insights pertaining to the development of Grand Inga are drawn from scenarios assessing:

a) Different extent and timing of the project’s development (i.e. scenarios assume either completion of just the committed Inga III Low-Head – 5.5GW - or a full-scale continued project development over time);
b) Different levels of cross-border interconnection across the African continent;
c) Different levels of final electricity demand for the entire African continent (only in the aggregated model);
d) Different costs for constructing or operating the project (only in the aggregated model).

2.4.3 Cyprus – An isolated grid system

The case of Cyprus is quite interesting in that it is an EU member state that has relied on oil-fired generation for several decades but has reached a point at which it recognizes that a fuel shift is necessary. This would allow conformation with European Union and international directives and improve energy security. A derogation on the level of SOx emissions ends in 2020, at which point the use of heavy fuel oil (HFO) with high sulphur content will no longer be possible to the extent currently used; this affects about 80% of the current generation mix [103]. Deployment of RET can assist in meeting these targets, while it also addresses the renewable energy sub-target of SDG7. Contrary to the case of Africa, there is enough capacity to meet electricity demand [104] but the system is largely outdated, inflexible and highly-polluting, as the vast majority of the generation originates from plants fired on heavy fuel oil [105]. Further, substantial gas reserves have been discovered offshore but production has not started yet.

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19 The use of this term arises from work conducted with the government of Cyprus, part of which is presented in paper VI. Specific unit performance data is classified and cannot be publicly disclosed.
The small size of the internal energy sector means that gas export markets have to be secured first. In the meantime, authorities are assessing the option of gas imports.

Furthermore, concerns emerge as to the volume of fluctuating RET to be introduced in the system. The share of renewable energy is slowly increasing in the generation mix in recent years; from 3.3% in 2011 to 8.5% in 2015 [107]. The main challenges in the deployment of variable RET in Cyprus arise from the lack of a grid interconnection and the technical inability to operate the existing thermal power plants in a highly flexible manner\(^\text{20}\). Even with the current share of below 10% in the generation mix [86], abrupt changes in the generation level from RET pose a challenge for the local Transmission System Operator, who occasionally resorts to curtailment of renewables to ensure grid stability.

Investments in large scale infrastructure are required to transform the power sector of the island. Deployment of RET is a necessity to achieve national and EU targets and can allow achievement of international air pollutant emission targets. At the same time, this would help achieve the renewable energy sub-target of SDG7. However, investments in fossil fuel infrastructure are expected to occur as well. Gas pipelines or regasification terminals are required to land natural gas on the island, either from the domestic off-shore reserves or via imports. Once gas-fired generation is available, it can compete against RET in the achievement of emission targets. Future deployment of RET and potential associated storage options require capital investments. The quantification of renewable energy that will be able to compete effectively in an open electricity market is crucial for appropriate sizing of this infrastructure.

Scenarios of maximizing selected economic gains from offshore natural gas reserves in Cyprus along with neighboring Israel are assessed in Paper V. This also acts as an initial attempt to comprehend the potential evolution of the island’s energy system. In Papers VI and VII the potential contribution of RET in the Cypriot generation mix is evaluated for a range of scenarios. This country-specific case study provides a focus on national

\(^{20}\) Based on personal communication with officials in the Cypriot Transmission System Operator and the Electricity Authority of Cyprus.
specificities that become prominent when a detailed analysis is conducted in close collaboration with local stakeholders. Cyprus is chosen due to its grid isolation, as the associated challenges in the deployment of variable RET can offer interesting insights. Another interesting aspect is the competition between RET and a potential introduction of other energy carriers, such as natural gas, when looking into a transition towards a low-carbon economy.

An array of scenarios is developed for this case study, reflecting the various alternatives faced by energy policy makers on the island. The analysis conducted looks into:

a) Potential introduction of natural gas in the electricity supply system;
b) Different timing for introduction of natural gas in the system. This affects the achievement of renewable energy and industrial emission targets in 2020;
c) Different levels of final electricity demand;
d) Potential development of large scale gas transformation infrastructure (i.e. gas liquefaction terminal or gas-to-liquids). This affects the level of final electricity demand;
e) Development of an interconnector with Israel and Greece.

Selected results from the case studies are provided in chapter 3 of the thesis, while results for the scenarios mentioned above are available in the appended papers.

2.5 Data and assumptions limitations

An understanding of the local specificities in each study is of importance; especially so in the case of optimization models, where utilized data and assumptions affect model outputs substantially. One limitation of the African and Grand Inga case studies is that there was no collaboration with national authorities\(^{21}\); only with international organizations active in the

\(^{21}\) Specifically, collaboration with United Nations Economic Commission for Africa (UNECA) and the International Renewable Energy Agency (IRENA) benefited the relevance of the model outputs.
region. With regards to model development, information has been gathered primarily from public domain data sources. For instance, generic investment and operation and maintenance cost have been used instead of country- and plant-specific data. Nevertheless, model development has been carried out with the purpose of building a basis upon which local governments and researchers can expand and improve in the future.

On the other hand, research carried out for the case-study of Cyprus was undertaken with the close collaboration of local government authorities and the power utility. Thus, access to comprehensive country-specific data was possible. Additionally, the interaction with local energy planners was an invaluable experience for the author, as it provided a deep understanding on the objectives of each relevant stakeholder. Furthermore, insights were gained on the strengths and weaknesses of the existing science-policy interface and how the decision-making process is affected by such quantitative studies.

The key assumptions and data used along with a description of the main parameters are provided in the appended papers. Even though some of these parameters are changed in the scenarios within each analysis, others remain constant. For instance, a fixed discount rate has been adopted in each analysis. The discount rate defines the cost of borrowing capital, which is important when assessing the competitiveness of capital-intensive infrastructure, such as RET.

In all the case studies, the author was faced with the dilemma of spending a significant amount of time seeking exact values for each parameter or focusing on key decision variables. Since time for study completion is often limited, compromises have to be made. Weaknesses in the input data used are to an extent addressed through the use of scenarios, for which explicit description is given in preceding sections. Such limitations are common, even in ‘best practice’ analysis [108].
3 Results

This chapter of the thesis is a compilation of results and insights gained from the associated analyses. Results are first presented for each case study individually, before common conclusions are drawn from across the thesis.

3.1 Exploring RET competitiveness under a range of scenarios

The discussion provided here is based on selected results from across the case studies. Even though most of these results are available in the appended papers, they are also presented here with the aim to address the research questions posed in section 1.2.

3.1.1 Unlocking the RET potential of Africa

A substantial capacity increase in RET is foreseen by the analyses conducted for the African case. Investments occur in both hydro and non-hydro RET across the continent. Technology choices and the resulting generation mix vary between regions and countries, but also between the two models with different degree of system representation.

3.1.1.1 The potential role of RET in increasing electricity access in Africa

Initially, using a five-region model of Africa’s electricity supply, two scenarios of varying GDP growth rates are formulated. A correlation is assumed to exist between GDP and final electricity demand, thus two different electricity demand projections are used in these scenarios. In order to increase electricity access and meet the rising demand, investments in generation infrastructure are required. This is evident by the increase in generation capacity for both cases (Figure 3), which by 2030 leads to generation shares by RET of 42% and 55% in the High and Low GDP scenarios. Even though these results show that capacity of fossil fuel fired technologies increases over time, capacity of hydro, as well as non-hydro RET, increases substantially by 2030. This indicates that deployment of RET can play an instrumental part in improving electricity supply in a cost-optimal way.

22 Referring to the analysis done in Papers I and II.
Annual investments in the High GDP case range between 33 and 86 billion USD during the period 2015-2030. In fact, when deployment of non-hydro RET is limited in the High GDP scenario (Figure 4), the overall system cost increases substantially. Figure 5 illustrates the difference of the various cost components of the system. Net negative costs indicate lower costs in the scenario where non-hydro RET are not constrained, whereas net positive costs indicate higher costs for the same scenario. Despite the higher investment cost when RET deployment is allowed, significant overall cost savings can be achieved, primarily through avoided fuel costs. In other words, bulk supplies of RET play a vital role. They lower the system costs, which can translate to more affordable power supply. In a region where both increase supply and affordability are critical.

Figure 3 – Total installed capacity by technology in two different GDP scenarios for Africa.

Figure 4 – Generation mix in 2030 across Africa in the High GDP scenario with and without non-hydro RET investments allowed in the model.

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23 Results shown based on the High and Low GDP scenarios of Paper I.

24 Results shown based on High GDP scenario of Paper I.
3.1.1.2 **The importance of trade on RET deployment in Africa**

In order to evaluate the role of interconnector availability in unlocking unexploited renewable energy potential across the African continent, different trade scenarios are developed. One scenario assumes that only existing and committed interconnector projects are available, while the other assumes that additional interconnector projects will be identified and developed in the future. These scenarios are analyzed in both the aggregated and the national scale model of Africa. Results from the latter modelling activity are shown in this section.

A higher trade potential allows significantly higher contribution from hydropower in Central Africa and geothermal and biomass-fired generation in Eastern Africa (Figure 6). In turn, this additional electricity is exported to the Northern, Southern and Western African power pools. When investments in trade interconnectors are limited, the former importing countries increase domestic generation from gas, coal and solar thermal facilities. This illustrates the role of increased trade in tapping into low-cost RET in isolated parts of the continent (in terms of grid interconnections). On the other hand, a limited interconnector availability

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25 Results shown based on High GDP scenario of Paper I.
results in the deployment of costlier fossil-fired and RET generation options. This becomes more apparent when the costs of the two scenarios are contrasted (Figure 7). In an Enhanced Trade case, additional investments occur in transmission and generation infrastructure to exploit renewable energy potential in remote areas of the continent. In turn, this leads to lower fuel costs and hence lower cost of electricity generation.

Figure 6 – Technology choice and generation mix differences between an Enhanced and a Limited Trade scenario in Africa.\textsuperscript{26}

\textsuperscript{26} Results shown based on the two scenarios of Paper II.
3.1.1.3 Spatial granularity and its effects on trade representation

In the case of Africa, which is treated as an interconnected system, optimization is conducted over the entire system. This entails that investments can occur in one country to provide electricity for another country, so as to reduce the overall system cost. Exchange of electricity between countries or power pools then takes place based on the marginal price of generating electricity on the two sides of the interconnector at each particular point in time. If the marginal price is lower in country A than country B, then additional investments or dispatch of existing generation options occur in country A beyond the level required to meet endogenous demand, in order to meet electricity demand in country B. In this manner, projects of common interest can be highlighted, leading to potential common efforts for mobilization of funding and power purchase agreements. As illustrated in Figure 8, when the model setup aggregates

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27 Results shown based on the two scenarios of Paper II.
countries into power pools, it is difficult to estimate the specific trade potential between countries.

When moving to the national scale model, the detail increases. Figure 9 illustrates electricity flow between countries in an Enhanced Trade scenario. A representation of the system at the national scale brings up aspects that would otherwise be missed. One such aspect is the role of transit countries. For instance, Ethiopia exports electricity to Sudan, which is then transmitted further to Egypt. In this example, in 2030 about 50 TWh of electricity are exported from Ethiopia to Egypt via Sudan. This volume of electricity corresponds to one sixth of the electricity generated in the whole Eastern African Power pool that same year. By being able to

Figure 8 – Indicative electricity trade (TWh) between power pools for an Enhanced trade scenario in 2030 in the aggregated five-region model of Africa.  

28 Results shown based on the Low GDP scenario of Paper I.
identify trade potential at this level on an annual basis, the timeframe by which grid interconnectors should be available can be established.

3.1.1.4 The effect of spatial granularity on technology choices in Africa

With regional aggregation of national grid systems, each region is treated as a common pool with limitless electricity trade between the grouped

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29 Results shown based on the Enhanced Trade scenario of Paper II. Space limitations in this thesis do not allow a bigger size for this figure. A more legible format is provided in Paper II. A gap between the ribbon and associated colour segment refers to electricity imports for the respective country. Electricity starts flowing from a country without this discontinuity. The colour of the band is identical to that of the country of origin, which is identified by the colour of the inner-most circle.
systems. In reality, however, grid interconnector congestion may exist that disallows electricity exchanges beyond a certain level. This has repercussions on the assumed RET potential that can be exploited within such an aggregated power pool, potentially leading to over-estimations. For instance, the Central African power pool has an unexploited hydro potential corresponding to more than 1,000 TWh annual generation [101]. The aggregated five-region model assumes that this potential can exist anywhere in the power pool, when in actual fact more than 260 TWh exist in the Democratic Republic of Congo alone due to Grand Inga [101]. As such, consumption, and hence demand, of Inga electricity within the power pool should be limited by the level of interconnection between countries.

Aggregation of countries into a single power pool disregards any trade limitations between these. As such, it can be hypothesized that in a cost-optimization model cheap energy resources anywhere within the region will be exploited to their maximum possible extent. As such, deployment of RET could be overestimated, beyond levels that could realistically be achieved without significant investments on required cross-border transmission links.

As specific assumptions regarding penetration rates of new technologies and final electricity demand differed between papers I and II, results were not immediately comparable. Thus for this cover essay the aggregated
Africa model was re-calibrated by aligning selected assumptions, such as electricity demand, used in the national-detailed model and reported in Paper II.

As shown in Figure 10, when assumptions are aligned between the two models, the results of the power pool model change towards lower fossil fuel use and consequently a higher RET share, especially in the case of wind, geothermal and solar PV technologies. Looking at the results of the two models, a series of significant observations can be made. First of all, in the regional model, resources that are cheap or abundant in a particular country within a region become highly exploited throughout the region. This applies to coal in Southern Africa, natural gas in Northern Africa, wind in Eastern and Northern Africa and hydro in Central Africa. This confirms the intuition that in the absence of trade boundaries within a power pool, the potential exploitation of cost-competitive resources may be exaggerated by an aggregated model.

Secondly, the type of technologies that is deployed changes. Distinct examples include solar PV and solar thermal, which have a much higher contribution in the detailed model, whereas wind, hydro and fossils have a lower contribution. This is because the least-cost options deployed in the aggregated model cannot be fully exploited when the grid interconnectors are a limiting factor. Instead, less cost-effective options are chosen. Similarly, distributed solar PV appears more competitive in the national-scale model, as grid-connected technologies collectively lose in competitiveness when there is the need for grid expansion and as such the associated costs are defined in further detail. Similarly, when grid extension costs are explicitly included off-grid options appear attractive.

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33 Assumptions on maximum technology deployment rate and final electricity demand were aligned to those reported in Paper II.
Figure 10 - Generation (TWh) by each technology group at the aggregated power pool and national level models for a high trade scenario in 2030. Results are compared following alignment of model assumptions\textsuperscript{34}.

When looking at specific power pool results, noticeable variations include the following:

a) Hydropower generation in Central Africa is lower by 25\% in the national scale model. This leads to lower electricity exports to other power pools.

b) Wind generation in East Africa is reduced drastically when the spatial resolution is increased, having an equivalent effect on electricity exports from the region.

\textsuperscript{34} Results shown based on the High GDP scenario of Paper I and the Enhanced Trade scenario of Paper II.
c) Gas-fired generation in West Africa is reduced in the national scale model. Contrary to the cases of Central and East Africa, RET deployment in this case increases, as the gap in generation is filled by solar thermal and solar photovoltaic technologies.

The main message from this is that the degree of system granularity greatly affects the mix of technologies that is chosen. This demonstrates the utility offered by increasing geospatial detail when assessing, for instance, on-grid versus off-grid technologies for electrification purposes [109]–[114]. Such tools only offer insights on snapshots in time and a combination of long-term energy system models with geospatial analysis could potentially benefit both.

3.1.2 Grand Inga and associated potential for electricity exports

Next, the largest potential hydro RET project proposal in the world (and the focus of papers III and IV) is examined. The extent of development of the Grand Inga has a direct effect on the availability of low-cost electricity exports from DRC. This section presents results from the Grand Inga analysis making use of the national-scale model. The scenario description is available in the relevant paper, but the key attributes are repeated in Table 1. The two key variables in these scenarios are the extent of project completion during the study period and the grid interconnector availability across the continent.

| Table 1 – Scenario assumptions in national-scale Grand Inga analysis (Paper IV). |
|---------------------------------|-----------------|-----------------|-----------------|
| Scenarios                       | Limited Project Development | Continued Project Development | Limited Trade |
| Maximum Inga installations (2020-2050) | 5,456 GW | 30,214 GW | 30,214 GW |
| Interconnector availability     | Extended        | Extended        | Limited        |

When comparing a Limited with a Continued project development case, a visualization of the difference in export potential from the project is provided (Figure 11). Even with the partial completion of Grand Inga’s next
three phases by 2040 (totaling about 15.4 GW)\textsuperscript{35}, 50 TWh of electricity are freed-up for export. This volume of electricity corresponds to 21\% and 3\% of the electricity generated in Central African Power Pool and Sub-Saharan Africa respectively for that same year.

![Limited project development](image)

![Continued project development](image)

Figure 11 – DRC’s generation mix until 2040 in a limited Grand Inga (top) and a continued project development scenario (bottom)\textsuperscript{36}.

\textsuperscript{35} A brief description of the proposed stages of development and the associated capacity additions is available in Paper IV - Regional effects of Grand Inga: A project-focus application of TEMBA (The Electricity Model Base for Africa).

\textsuperscript{36} Results shown are based on Paper IV.
The extent of project development and the excess electricity generated (i.e. beyond DRC’s final electricity demand) highlight the necessity for interconnector development. As new generation capacity installations occur, investments in transmission infrastructure are required to enable the foreseen electricity exports. Next the interconnector requirements calculated from the national-scale model are reported.

In a Limited project development scenario, assuming that the upcoming phase of the project is completed, at least 4 GW of interconnector capacity is required by 2030 to-and-from DRC (Figure 12). Comparable capacities are reached in the other two scenarios for the same year. This is because the next phase of project development occurs in all scenarios by 2023.

![Figure 12 – Capacity of interconnectors with DRC in each scenario](image)

By 2040 capacity of the interconnectors increases to a small degree in a limited project development case. This is because investments in Grand Inga stop in 2023 in this case. However, as the project continues to be developed in the other two scenarios, capacity of the interconnectors increases by 2040; reaching 9.2 GW in the Continued project development scenario and 6.5 GW in the Limited trade case. It should be noted that the

37 Results shown are based on Paper IV.
latter figure corresponds the maximum interconnector capacity allowed in this scenario; hence the same capacity is observed by 2050.

Differences in interconnector capacity between the Limited and Continued project development scenarios indicate the importance of generation infrastructure deployment for the demand of corresponding transmission infrastructure. The opposite can be said when comparing Grand Inga’s capacity additions between the Continued project development and the Limited trade scenarios. When potential for trade is limited, there are not enough routes to allow substantial electricity exports, thus affecting the viability of the Grand Inga project. This is more pronounced when looking at cumulative capacity installations in 2050 (Figure 13). By this point, capacity additions are higher by 12 GW when an extended interconnector availability is assumed.

![Figure 13 – Cumulative capacity additions of the Grand Inga project in each scenario](image)

**The effect of spatial granularity on Grand Inga project development**

Insights offered by the different levels of spatial resolution on Grand Inga development are comparable to those discussed above for the broader Africa case. When the spatial resolution is increased, the direction in which Inga’s electricity trade flows changes. Whereas in the five-region model

38 Results shown are based on Paper IV.
electricity is primarily exported to Southern African Power pool and then to Western African Power Pool, this is not exactly the case in the more detailed model. In the results of the national-scale model, South Africa remains the primary consumer of Inga’s electricity, but a substantial volume of electricity is exported towards the Eastern African Power Pool. This change can be attributed to congestion caused by grid interconnector capacity connecting DRC to Nigeria (i.e. the biggest consumer of electricity in West Africa), as well as low prices for gas-fired generation in Nigeria.

Another important dissimilarity relates to the extent of Grand Inga development in the models with varying granularity. In a limited trade scenario, where capacity of interconnectors is limited to existing and committed projects, the two models produce quite different scenarios. Whereas capacity of Grand Inga reaches 17 GW by 2040 in the aggregated model, it only reaches 14 GW in the same year and 15 GW by 2050 in the national scale model. In the latter case, capacity is limited by the internal electricity demand in DRC and the availability of interconnectors for power exports. On the other hand, the coarser resolution of the five-region model allows Inga’s electricity to satisfy the electricity demand of other Central African Power Pool systems (e.g. Cameroon, Congo and Gabon)\textsuperscript{39}. These results provide a strong indication that a national-scale resolution is needed in models assessing the potential viability of generation projects, from which a substantial share of the electricity will be sent for exports.

3.1.3 The outlook for RET deployment in Cyprus

As mentioned previously, an imminent transformation of the electricity supply sector is expected in Cyprus. Renewable energy and CO\textsubscript{2} emission targets set by the EU and international industrial air pollutant emission targets will force the system to move away from the current generation mix. In a scenario where only the current fuel choices are available, in order for the system to meet binding emissions targets and keep the cost of

\textsuperscript{39} This is a simplification connected to the scope of the initial analysis of the five-region model. This focused on the impact of the project on Central Africa and the rest of the continent as a whole; thus, additional detail was not required.
electricity at low levels in the longer term, RET deployment has the potential to increase sharply.

As shown in Figure 14, the introduction of stricter environmental regulations shift the system away from the current HFO-fired generation to fuels with lower sulphur content; namely diesel and HFO with low sulphur content. These fuels however are more expensive which brings the cost of generation from the existing thermal plants at higher levels. As such, RET gain in competitiveness and increase their contribution over time. The renewable energy share in generation in this case increases from 8.5% in 2015 to 18% in 2020 and 52% in 2030. The most cost-competitive RET option are photovoltaics as they contribute to 43% of the generation in 2030.

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40 Results shown are based on the PO (No-gas) scenario of Paper VII.

41 For a detailed description of the particular scenario and model assumptions, please refer to Paper VII – Natural gas in Cyprus: the need for consolidated planning.

42 Currently the HFO fired contains 1% Sulphur by weight. In these results, by 2020 HFO will have to be acquired with a sulphur content of either 0.5% or 0.23%.
This entails a substantial addition in intermittent RET over a relatively short period in time, in an isolated grid system. Storage options, namely pumped hydro storage and Li-ion batteries are deployed to cope with RET variability. However, concerns regarding system reliability and stability arise as to whether the existing grid and thermal technologies have the necessary flexibility to manage such a sheer volume of RET. A parallel grid stability analysis conducted by JRC for the Republic of Cyprus has shown that this is possible [115]. RET and storage deployment levels in a comparable scenario as the one shown here were assessed and proven to be technically feasible.

Despite the results shown above, the notion that RET will simply be the optimal solution to move away from oil may be misplaced. There are other low carbon options available. The following subsections examine the effect of gas introduction in the Cyprus electricity mix.

3.1.3.1 Potential domestic production of gas and exports

One aspect that has the potential to transform the entire energy outlook of Cyprus relates to the discovery of offshore gas reserves. At the same time Israel, which shares a maritime border with Cyprus, has made substantial gas discoveries and has already started production [106]. The quantity of proven reserves in Cyprus is such that exports of gas will be necessary for the commencement of production, as energy demand in Cyprus is too low to absorb the estimated volumes [116]. Exploitation of gas reserves and export sales have multiple configurations. Gas can be liquefied, converted into petrochemicals or fired to generate electricity. These can then be sold to the international market, upon development of the necessary infrastructure; in essence, a liquefaction terminal, a gas-to-liquids facility or a grid interconnector to other systems. These options are evaluated in the context of common exploitation of gas reserves between Cyprus and Israel[43]. A set of scenarios examines the form of exports that is more cost-effective under a range of gas and electricity prices (Table 2).

43 Referring to the analysis conducted in Paper V - Energy Security prospects in Cyprus and Israel: A focus on Natural Gas.
### Table 2 – Cumulative LNG and electricity exports by Cyprus and Israel by 2050 across a range of commodity price scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cyprus LNG (GWh)</th>
<th>Cyprus Electricity (GWh)</th>
<th>Israel LNG (GWh)</th>
<th>Israel Electricity (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline prices</td>
<td>1 124 072</td>
<td>150 434</td>
<td>4 386 202</td>
<td>202 004</td>
</tr>
<tr>
<td>Grid interconnector expansion</td>
<td>748 741</td>
<td>326 511</td>
<td>4 050 381</td>
<td>278 427</td>
</tr>
<tr>
<td>Higher LNG prices (+50%)</td>
<td>1 525 107</td>
<td>0</td>
<td>4 979 299</td>
<td>123 254</td>
</tr>
<tr>
<td>Higher LNG prices (+100%)</td>
<td>1 580 604</td>
<td>0</td>
<td>5 511 715</td>
<td>100 736</td>
</tr>
<tr>
<td>Higher electricity prices (+50%)</td>
<td>722 678</td>
<td>344 245</td>
<td>3 232 870</td>
<td>146 230</td>
</tr>
<tr>
<td>Higher electricity prices (+100%)</td>
<td>688 264</td>
<td>362 878</td>
<td>3 232 870</td>
<td>242 439</td>
</tr>
</tbody>
</table>

Results from this analysis indicated that the electricity supply sector of the two countries would gradually be dominated by gas-fired generation. Substantial economic gains are to be had from exports of gas; either in the form of electricity or LNG. Further, the analysis was conducted during a period of high oil prices. As such, the option of developing gas-to-liquids facilities and exporting petrochemicals was also deemed as a viable option. Nonetheless, the infrastructure of any form of export is lacking in both countries and significant investments are required.

RET model representation, which is the focus of papers VI and VII, in this analysis is conducted in a simplistic manner, where technology learning rates are not defined for these generation options. The focus is on natural gas dynamics associated with its utilization\(^44\). Subsequent papers revert to

\(^44\) Thus, minimal investments in RET occur in this model, reaching a generation of about 950 GWh from these options, corresponding to about 13% of the total generation in 2020. It should be noted that national targets, such as the 16% RET share in generation for that year [83], are not included as minimum limits in the analysis. Post-2020, after new gas-fired plants are allowed in the model, the renewable energy share decreases and revolve around 6% for the majority of the model period. These limitations make a
a deeper analysis of RET and the role of technology learning, gas, system variability, and various directives.

### 3.1.3.2 Gas introduction and its effects on RET deployment

Competitiveness of RET is affected directly in case gas is introduced in the system. Following the recent sharp reduction in solar PV costs [85], the focus of the work is expanded to encompass RET and thermal power plants in considerably further technical detail.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Demand</th>
<th>Gas arrival</th>
<th>Gas Liquefaction</th>
<th>EuroAsia Interconnector</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>High</td>
<td>2023</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC2</td>
<td>Low</td>
<td>2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC3</td>
<td>High</td>
<td>2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC4</td>
<td>High</td>
<td>2016</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>SC5</td>
<td>High</td>
<td>2016</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>SC6</td>
<td>High</td>
<td>2016</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

Table 3 – Scenario attributes used in the Cyprus IRENA study.

Table 3 gives a brief overview of the scenario characteristics used in the subsequent output of this thesis (i.e. Paper VI) that informed IRENA’s Renewable Energy Roadmap for the Republic of Cyprus [21]. These affect the analysis considerably. Final electricity demand directly affects the required level of generation. The date of gas availability affects achievement of industrial air pollutant targets in 2020. The development of a gas liquefaction terminal would increase the island’s electricity demand considerably, while a grid interconnector could facilitate introduction of higher shares of RET. All these scenarios assumed availability of natural gas at the time of writing as a fuel for electricity generation, either by 2016 or by 2023. Gas can provide multiple benefits in the context of the island’s energy supply. Its cost per unit of energy is typically lower than oil [16], while it has a lower Sulphur content [117] and lower CO$_2$ emission factor [29].

detailed further analysis of the power sector necessary so as to assess the cost-optimal level of RET deployment under a range of scenarios.
The share of RET in generation decreases significantly in case gas is introduced in the system. By 2030 the highest RET share in the analysis reaches a maximum of 40% in the scenarios with interconnector development (Figure 15), significantly lower than the 52% share in the scenario without gas presented in the preceding section. In fact in scenarios (SC1 and SC3) with equivalent assumptions as this no-gas scenario, the RET share is confined to 26% in 2030. This substantial difference suggests that the substitution of oil with a cheaper, lower-carbon fuel has direct effects on the potential deployment of RET.

Another aspect that emerges from the results of this analysis is that of timing of investments. Two scenarios are compared where the only parameter that changes is the year in which gas is made available in the Cyprus market; 2016 in one case and 2023 in the other. The rate at which RET are deployed changes between these two dates (Figure 16).

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45 In terms of final electricity demand and grid interconnector availability.

46 Results shown are based on the six scenario of Paper VI.
Specifically, by 2020, solar PV capacity increases to 427 MW when gas is not available versus 200 MW when gas is available. In terms of generation, the share of renewable energy reaches 28% in the former and 18% in the latter case for the same year. This difference is attributed to the necessity to cut down SO\textsubscript{x} emissions by 2020 and the associated unavailability of low-cost HFO with high sulphur content. It is thus evident that the date of gas availability has a direct impact on the medium-term deployment of RET; in this case solar PV. It is interesting to note that once gas is available, deployment of solar PV converges in the two cases as the installed capacity of this option is the same from 2025 onwards.

Figure 16 – Solar PV capacity in Cyprus in scenarios where gas is available in 2023 (SC1) versus 2016 (SC3) \(^{47}\).

3.1.3.3 Gas deployment scenarios

The form in which gas will become available to the island at the time of writing had not yet been established. Gas could be made available via pipelines from the offshore reserves once production starts or the fuel could be imported as LNG and then re-gasified before being fired for generation. Another option could be a hybrid of these two choices. The final

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\(^{47}\) Results shown are based on scenarios SC1 and SC3 of Paper VI.
output of this dissertation\textsuperscript{48} examines the impact of each alternative on the generation mix and the average cost of electricity generation in Cyprus. Detailed results, scenario description and discussion are provided in the respective publication, so they will not be repeated here. Instead, an overview is given of an expansion of that work. It was for authorities in Cyprus to illustrate the utility and policy relevance of the conducted analysis. This analysis is largely based on the equivalent assumptions of Paper VII. Deviations from this are provided in Appendix A of the thesis.

A model is constructed for the entire energy system of the island and the modelling horizon is expanded to 2050. Modules representing the transport and heating and cooling sectors are connected to the existing electricity module. Outputs for the electricity supply sector from three scenarios are presented here. The identified scenarios, along with respective data and assumptions, were agreed with local authorities in Cyprus and are the following:

- **Early Gas Scenario**: Natural gas is available via an LNG regasification terminal by 2019.
- **Delayed Gas Scenario**: Natural gas arrival is delayed to 2024.
- **No Gas Scenario**: Natural gas is not made available at any point in time. Since, currently about 90\% of the generation is oil-fired, this is the most demanding scenario in terms of emissions reduction, as CO\textsubscript{2} and SO\textsubscript{x} emissions are higher for oil as compared to gas.

As illustrated in Figure 17, the share of RET increases in all scenarios. By 2020, the share of RET in generation is 18\% in the Early and Delayed Gas scenarios, while it decreases to 16\% by 2030. In the No Gas scenario, however, in order for the system to meet binding emissions targets and keep the cost of electricity at low levels in the longer term, RET deployment increases sharply. The share of RET in generation reaches 31\% by 2020 and 56\% by 2030, where it remains at the same share until 2050. As seen previously, availability of gas keeps the RET share at lower levels. In the Early and Delayed Gas scenarios, RET share increases gradually to 37\% by 2040 and 40\% by 2050.

\textsuperscript{48} Paper VII – Natural gas in Cyprus: the need for consolidated planning
The use of storage by the model provides important insights. As illustrated in Table 4, storage is invested in even at lower levels of RET deployment. Having taken part in numerous discussions with stakeholders in Cyprus, there is the perception that storage will inevitably be needed as the share of renewable electricity increases and as such the cost should be borne by RET investors [118]. However, the argument is complicated by the results. During the period 2026-2030 in the Early Gas case, when RET share is steadily around 15%, investments in storage options occur. These provide a benefit to both RET, but also to conventional thermal generation. In the former case they deal with intermittency of RET. In the latter, they allow the system’s highly efficient Combined Cycle Gas Turbines to work at higher loads for longer durations in time. Instead of ramping down or completely shutting off these units during periods of low demand, the model results indicate that it is cost-optimal to store energy at such times and release it during periods of higher demand. In this manner, low-cost electricity from RET as well as these facilities is stored. In certain (but not all) instances, therefore, batteries are also used to provide peak power, as well as reducing reliance on less efficient oil based power plants. The model results are no doubt sensitive to specific cost and flexibility assumptions that are subject to change. An important insight, however, is that the market structure that would be needed should reward grid services such as
storage, based on its merits in the system and not simply an extra cost for RET investment.

It is important to mention that the annual peak electricity demand coincides with the period with peak generation from solar PV, i.e. the summer season due to space cooling. Since solar PV is the RET option that is most deployed in all scenarios, its deployment reduces the volume of peak electricity that must be met by fossil fuel-fired generation.

Table 4 – RET share in generation and storage deployment in selected years in the Early Gas scenario.

<table>
<thead>
<tr>
<th>Historic</th>
<th>Early Gas Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>2025</td>
</tr>
<tr>
<td>RET share</td>
<td></td>
</tr>
<tr>
<td>8.5%</td>
<td>16.4%</td>
</tr>
<tr>
<td>Storage (MW)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Storage (MWh)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Important insights are offered by the calculated CO₂ emissions of each scenario (Figure 18). A limit on CO₂ emissions in the electricity supply sector is introduced from 2030 onwards, based on the European Union emissions reductions target for the ETS (Emission Trading Scheme) sector⁴⁹ [119]. In the absence of agreed targets beyond 2030, the limit on emissions is kept constant for the entire model horizon - until 2050. This limit is overachieved in all scenarios. However, by 2050 the No Gas scenario has the highest emissions, despite the high RET share: 56% as compared to 40% in the other two scenarios, which are slightly less emitting. However, since the EU has articulated targeted emission reductions of 80% by 2050 compared to 1990 levels [120], further investments will be necessary. This necessity can increase the level of RET even further, promoting other low carbon technologies such as nuclear and carbon capture and storage (CCS), or lead to the introduction of energy efficiency measures. The cost, social acceptance and techno-economic

⁴⁹ A 43% reduction on emissions is envisioned by 2030 as compared to 2005 levels.
viability varies for each of these alternatives and can be the subject of numerous future analyses.

![Figure 18 – CO₂ emissions in electricity supply for three gas availability scenarios in Cyprus](image)

The cost of electricity generation is estimated in each scenario (Figure 19). This is important as it enables policy makers to visualize the cost of different development pathways. Two aspects are highlighted by these results. Firstly, the vast deployment of capital-intensive RET in combination with the high fuel cost for oil-fired generation in the No Gas scenario leads to the highest cost of generation in the three scenarios. The difference with the lowest scenario (i.e. Early Gas) is as high as 23% in 2021 and 21% in 2040. The second, more immediate, aspect of importance relates to the necessity to cut down SOₓ emissions by 2020. In a delayed gas scenario, expensive fossil fuels with low sulphur content will have to be used. This leads to considerably higher electricity prices in the period 2020-2023 than if gas were to be available (i.e. Early Gas scenario). The difference between the Early and Delayed Gas scenarios exceeds 20 EUR/MWh; this translates to a difference of 25% between the two cases. The timing of gas arrival affects not only the cost of electricity, but also the cost-competitiveness of RET. As indicated by the No Gas scenario, an indefinite delay of gas availability for generation makes a substantial deployment of RET as the cost-optimum alternative.
Figure 19 – Evolution of average cost of generating electricity in Cyprus for three gas availability scenarios.

3.2 Common themes affecting RET deployment

Besides the aforementioned dissimilarity between the case studies of interconnected Africa versus isolated Cyprus, other differences arise beyond this that can affect investment decisions in the two systems. In connection to research question C, this section highlights variations as well as commonalities that may have implications on the feasibility of the cost-optimum energy mix as given by the model outputs.

3.2.1 Obstacles and opportunities for RET deployment

Economic development

The two focus areas of the thesis, the continent of Africa and Cyprus, are at two alternate stages of development. With a current GDP per capita at approximately $27,000, the Cypriot economy is proportionally much stronger and more stable than any African country. At the same time, the Democratic Republic of Congo, which is the location of the Grand Inga project, has a per capita GDP at approximately $450, which is one of the lowest in the world [121]. Therefore, the purchasing power of individuals and businesses is higher in Cyprus. Following a recent promotion of a net metering scheme for solar PV in residential, commercial and industrial
buildings, 9,000 installations have taken place. Since the population in Cyprus is roughly 840,000, this is a considerable addition. This would not be as easily achievable in countries with a much lower GDP.

Access to funding for the development of large scale projects is another important issue. As an EU member state and a member of the Eurozone, Cyprus is able to draw on funds from the European Central Bank and the European Investment Bank. Natural gas infrastructure in Cyprus and a potential electricity interconnector between Israel, Cyprus and Greece, as discussed in paper V, have been recognized as Projects of Common Interest that could receive EU support. Similarly, electricity supply projects in Africa have received financing from the World Bank in the past; this is especially the case for hydropower projects. In order to pursue sound investment decisions in the future, a study commissioned by the World Bank provided detailed analysis on whether climatic change could affect the generation output and hence financial viability of several future hydropower projects in Africa.

Even if some projects are to be financed through public funds or funds secured by development banks and international organizations, such as the World Bank, a substantial contribution from the private sector is necessary for the greenhouse gas emission reduction needed to mitigate climate change. In order to achieve the renewable energy contribution envisioned in the majority of scenarios presented in all the outputs of this thesis, private investments are necessary in Cyprus and across Africa.

Nonetheless, deployment of new RET projects is capital intensive and entails risks for investors, which are reflected in the cost of securing capital. Schmidt illustrates in a simplified manner how perceived risks affect the cost-competitiveness of low-carbon technologies adversely as compared to fossil-fired technologies. At the same time, the cost of capital is higher in developing countries than in developed countries, which leads to even greater risk for investments in these regions. This difference arises from a series of real or imagined technical, regulatory, financial and administrative obstacles that are more pronounced in

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[50] Figure retrieved from personal communication with the Ministry of Energy, Commerce, Industry and Tourism in Cyprus.
developing countries [128]. As a result, deployment of RET in the African context will be more challenging than in Cyprus; this does not mean that in the latter case, investors will not be wary.

In both contexts, policy measures are needed to reduce the perceived risks for private investors. An option for addressing financial risks would be the partial transfer of penalties associated with adverse incidents to public actors, such as development banks. This might be via the use of risk insurances or loan guarantees. In terms of reducing policy risks, ensuring functional institutions that support project application, permitting and implementation, and minimizing possibility of delays can provide an attractive environment for investments [127]. For a more elaborate description on de-risking options, the United Nations Development Programme has compiled a report on policy instruments that promote investments in RET by addressing investment risk, in which individual country case studies are provided as examples [128].

**Political context and conflicts**

An important limitation of this analysis is the political situation in each of the case studies, which has an effect on the perceived risks for investors. Many regions in Africa occasionally suffer from military conflicts and civil wars [129], which is far from ideal for the development and smooth operation of large scale capital-intensive infrastructure. Even the more economically-developed region of North Africa has recently experienced political instability and violence during the Arab Spring [130], which in many instances led to a change in the ruling regimes. In the context of this thesis, it is important to mention that Africa’s conflicts are often driven by struggle over the control of resources [129], [131]. Similarly, the resource-rich Democratic Republic of Congo has frequently faced political turmoil and conflicts both within and with neighboring countries. A recent example is the military intervention of Rwanda and Uganda in the period 1998-2003, during which warlords in the area profited from illegal trade of Congolese gold and diamonds [129], [132]. Undoubtedly, frequent conflicts in this Central African nation can pose a serious threat to the realization of the Grand Inga project.

In the case of Cyprus, the unsolved political Cyprus problem presents an obstacle in the exploitation of the offshore gas reserves, due to altercations with Turkey on the matter. Following the Turkish invasion of Cyprus in 1974, the Greek- and Turkish-Cypriot communities were split. The gas
reserves are under the control of the Republic of Cyprus, which is represented by the Greek-Cypriot community. Turkey argues that gas production should not commence until the Cyprus issue is solved, so that both communities can benefit from potential gas export revenue.

Additionally, in a prolonged low oil price environment, the oil and gas companies in charge of the test drilling are more cautious on investing time and capital in exploration efforts. Only one gas field has been found in Cyprus, whose volume does not justify Cyprus-own development of export infrastructure, such as a liquefaction terminal or a pipeline to Europe. Also, domestic demand does not justify the existing gas field production, so securing demand for the remaining gas volume is essential [116]. As such, in the absence of domestic natural gas and if imports are postponed indefinitely, RET have an important role to play in the achievement of Cyprus’s CO₂ and industrial air pollutant emission targets.

What’s more, a potential reunification of the two communities in Cyprus or at the very least a deeper collaboration between the two grid systems could potentially result in a transmission link to Turkey, thus solving the issue of isolation. In this manner, imports and exports of electricity would be possible, which can allow for greater shares of RET with reduced concerns on grid stability.

As indicated above, the case studies presented have in the past been the setting of violence and turmoil. An unstable political environment is unfavorable for investors as the risk for potential complications is higher. In such conditions, a faster rate of return on investment is often sought. Loans for development of the projects can have a high interest rate due to perceived higher risks, which can affect adversely the financial viability of capital-intensive RET projects in these countries. In future work, it would

51 Currently, exchange of electricity between the Republic of Cyprus and the Turkish-Cypriot community occurs only in periods of grave necessity, such as following the naval base explosion and the destruction of the Vasilikos power plant in July 2011 [133].

52 This is shown in scenarios SC5 and SC6 of Paper VI; the Cyprus IRENA Study.
be interesting to examine the effect of different discount rates\textsuperscript{53} on the cost-optimal technology mix in each case.

3.2.2 Scheduling of investments

The timing during which key infrastructure investments occur affects the rate of RET deployment. This is evident in the Cyprus context, where delayed arrival of gas makes investments in RET more attractive, so as to reduce generation cost and SO\textsubscript{x} emissions between 2020 and the first date of gas availability. In this case, RET benefit from delays in gas infrastructure development.

The Grand Inga case provides an example in which unavailability of transmission infrastructure has an adverse effect on RET investments. Delays in the establishment of grid interconnectors would mean that there’s limited potential for electricity exchange and hence the viability of the project is compromised. However, the opposite is also true. The rate of completion of the various stages of Grand Inga can have an impact on the level of expected electricity trade. As shown in Figure 20, a five-year delay in the project’s development has a noticeable effect on electricity exports from Central Africa to other power pools. In turn this would imply that potential already established interconnectors would be underutilized. Similarly, plans for additional enhancement of the grid network would be pushed further into the future.

Capturing these dynamics may not have been possible without the use of annual time-steps in the developed models, especially in the case of Cyprus. An annual resolution allows the visualization of investments decisions and associated implications on a year-to-year basis. Implications can include electricity cost hikes resulting from energy-planning decisions as the one shown for Cyprus in 2020-2023 in a delayed gas scenario (section 3.1.3.3).

\textsuperscript{53} Note that social discount rates used throughout the models are reported in each paper.
3.2.3 The importance of regional cooperation

A key theme that arises implicitly in the majority of the papers is that of regional cooperation. The establishment of an interconnection in Cyprus, holding all other things constant, allows for an increase from 26% renewable energy share by 2030 in a scenario without trade options to 40% in a scenario with possibility for trade for the same year (given the assumptions of the analysis). This increased RET deployment corresponds mainly to solar PV and assumes that at times when generation will exceed domestic demand, the excess can be transmitted to Israel or Greece. Similarly, it is assumed that during periods of low PV output, electricity can be readily procured from these neighboring systems. This assumes the existence of a framework through which the involved systems can trade at cost-efficient prices and volumes, similar to the way Nord Pool is structured. This Nordic power exchange currently operates in 9 countries (Nordics, Baltics, Germany and UK) and trades electricity between market participants at the intraday or day-ahead stages, as well as allowing for long-term contracts of up to five years. A similar approach

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54 Results shown are based on the Reference and Delayed Inga scenarios of Paper III.
55 The respective scenarios are SC3 and SC5 in Paper VI.
could be adopted for the development of an Eastern Mediterranean market in the future to facilitate integration of greater shares of RET in the region.

An equivalent prerequisite can be observed for Africa, where experience in regional liberalized electricity markets is low. Power pools have already been established with the aim of promoting electricity trade, but in Sub-Saharan Africa, only a handful of countries most notably hydro and wind in Eastern, hydro in Central, and solar and wind in Northern Africa.

Access to low cost-electricity through electricity imports can offer economic gains across countries. For instance, a reduction in electricity cost can make industrial products and commercial services cheaper within the importing country, which benefits the internal economy directly. Thus, political tension created between countries due to proposed project development might be alleviated by gains. One such example is the Grand Ethiopia Renaissance Dam, which has created conflict between Egypt and Ethiopia [66]. According to the results of the national scale Africa model, Ethiopian electricity can help in meeting Egypt’s demand in the future, as volumes of up to 40 TWh can be exported to the North African country by 2040 via Sudan, confirming the results of previous studies suggesting widespread economic benefits for the region by the project [77]. Nonetheless, other dimensions need to be recognized in this particular example. Water from the Nile river, upon which the hydropower project will be developed, is important for agriculture in Egypt. Further, a changing climate may affect precipitation, and in turn river flow and generation output from the dam [125]. These aspects are not accounted for in the thesis.

56 Specific examples include Mozambique, Zimbabwe and South Africa [28].

57 It should be clarified that in the developed model these exports are not necessarily from the Grand Renaissance Dam. But, could originate from other hydro or geothermal projects that get deployed in Ethiopia by that time.
In the Grand Inga analysis, where scenarios focus on a single project, Grand Inga provides an excellent example of how collaboration between countries is essential in the techno-economic viability of such a large-scale project. As shown in the results of the national scale model of Africa, if transmission links are not developed through transit countries to bring electricity to the main points of demand, the project cannot be fully exploited, thus keeping a low-cost electricity option largely untapped. As such, funding for the project and cross-border transmission links must be secured and ensuring demand for the electricity through power purchase agreements, as the one between DRC and South Africa [102], can facilitate in the procurement of the required capital. In this regard, the contribution of the national scale model in identifying potential markets under a range of scenarios should be highlighted at this point. Similarly, the recognition of the cost-optimum trade routes is of importance, as cooperation with transit countries will have to be sought for the development of the interconnectors. In this case it has been shown that trade routes through Angola, Namibia and Zambia towards South Africa, and towards several Eastern African states are the main links that seem to be cost-effective.

3.2.4 The potential role of storage

Storage is only modelled implicitly in the African case\footnote{58}, so insights in the African context cannot be drawn for this technology option. However, by focusing on the most technically detailed analysis within this thesis (i.e. the final output of the Cyprus case – Paper VII), certain observations can be highlighted regarding the future utility of storage as an enabler for RET.

In the conducted scenario runs, a pumped-hydro project of 130 MW is deemed as cost-competitive, not only for energy arbitrage, but also for provision of operational reserve. This centralized storage option can store electricity from variable RET in periods of high output, as a preferred alternative to curtailment. Additionally, if flexibility of existing thermal units in Cyprus is not improved and output from thermal plants cannot be ramped down or even shut off easily to accommodate variable generation, storage can be useful for the operation of these units as well. For instance,

\footnote{58 The time during which the battery options charge and discharge are predefined instead of letting the model decide on the optimum charging profile.}
the most efficient units in Cyprus are the combined-cycle gas turbines [105], but these cannot be turned on and off constantly as the cost of operation would increase dramatically. Instead, they could potentially be run constantly for long periods of time, even at low loads, making use of the storage infrastructure.

Therefore, it can be argued that centralized storage – while primarily an enabler for RET - can act for the benefit of the whole system. Control of the centralized storage to an extent can be handled by the Transmission System Operator (TSO), but the most complex issue is agreeing on which stakeholder would act as the investor of such a project and hence bear the financial risk. The market environment in which the project operator will function and generate profit has to be clear. Since a functioning liberalized electricity market structure is not yet in place in Cyprus, conditions are not ideal for investors. Generally, in Europe the legal framework of handling storage assets in unbundled markets is not perfectly clear as requirements such as grid support become more prominent [137]. Depending on the status of the network operator, a complete or partial ownership and operation by either the transmission and distribution system operator or a third-party is a plausible business model that allows provision of both network and market services [137]. On the other hand, in Africa where integrated companies own and operate both generation and grid network assets, it might be assumed that investment on centralized storage options will be handled by these entities as well.

Despite the fact that deployment of lithium-ion batteries is capital-intensive, it is calculated as economically optimal to also develop this storage option, as it allows for additional cost-competitive generation from variable renewable energy options at the final consumer level. In this case, a lower system cost is achieved through time of use arbitrage, where cheap electricity from solar PV can be used to charge the storage during the day and then be used during peak demand periods in the evening. Provision of ancillary services, in terms of operational reserves, increase the attractiveness of this technology as an option.

Further, lithium ion batteries can be deployed at both the centralized and the distributed level; for instance, at residential or commercial buildings. In order for the technology option to provide grid support, installation of ICT infrastructure is a prerequisite, as it assumes operation of a smart grid [137], which will have a cost associated to it. At the same time, even though
decentralized batteries can potentially offer both energy arbitrage and ancillary services for the grid, the cost of capital lies with the consumer. As such, incentives will have to be given to provide the market conditions for consumers to invest in such a technology and be willing to offer use of their infrastructure for facilitating in a smooth operation of the grid.
4 Conclusions

4.1 Concluding Remarks

This thesis provides applied analytical advances on specific case studies with a research focus on increasing the share of RET in electricity supply systems. By adopting existing methods to new settings (rather than developing new methods), novel information and insights are gained. These are related to RET deployment and integration in the case studies. Each one of the selected case studies presents a different set of situation-specific insights, indicating that there is no straightforward pathway towards higher RET adoption and integration. Through a comparison of the different models developed, it is shown that an increase in the dimensions and the details of the analysis affects the rate of RET investments foreseen in long-term cost-optimization models. A series of measures are required to facilitate investments in RET. Regional cooperation and defining a framework for storage are two of the aspects highlighted by the work.

The thesis showed that on the one hand spatial granularity affects technology choices and associated energy mix. This is an important consideration that should be considered when analyzing an undeveloped power system such as Africa’s. A high degree of aggregation can lead to an over- or underestimation of the cost-optimal share of RET. On the other hand, diversification of the energy mix through inclusion of other fuels, such as natural gas, can act as an alternative path towards a low-carbon economy. In the case of Cyprus, this has adverse effects on the level of RET deployment. In the developed scenarios, natural gas is more competitive than RET and acts as an intermediate transition fuel away from oil. Even though contribution from RET increases, availability of gas leads to a slower RET introduction.

A detailed technical representation is significant when high shares of variable RET are coupled with inflexible generation options, as in the isolated system of Cyprus. This helps to ensure that the results of the long-term energy system model suggest a technology mix that does not put the grid’s smooth operation at risk. It also suggests the need for nuanced market models for the introduction of supporting technologies, such as storage.
It is important to note that a major part of this thesis was conducted with
the use of open source data and tools. Energy policies driving the transition
to a low-carbon economy are based on outputs from such analyses. Hence,
public access to the approach and data used is essential in building trust
towards the experts and policy-makers [138]. This allows for research
results to be duplicated, discussed, challenged and improved, which
facilitate in reaching a consensus on the development pathways to be
chosen. As such this work does not provide a definitive ‘end-goal’. Rather,
it provides targeted contributions that add to the literature and provide a
basis for future work.

4.1.1 Thesis Contribution

A summary of the contributions to academic knowledge made by the
research outputs of the dissertation is provided in Table 5. Even though the
list is not exhaustive, it provides an adequate overview of the academic
advancements.

Table 5 – Summary of academic contributions

<table>
<thead>
<tr>
<th>Applied analytical advances include the following additions</th>
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<tbody>
<tr>
<td><strong>New Geographical scope covered by energy systems models</strong></td>
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<tr>
<td>- First Africa-wide optimizing bottom-up model available in academic literature (aggregated five-region model) including trade between power pools and considering all power pools.</td>
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<tr>
<td>- First open-access Africa-wide bottom-up model available in the academic literature with technology detail at the national level with potential for cross-border electricity trade. This was novel as it explicitly represented:</td>
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<tr>
<td>- First bottom-up model of Cypriot-Israeli gas reserves and with power trade between the two countries available in the academic literature.</td>
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<tr>
<td>- First open-access bottom-up model of Cyprus in the academic literature.</td>
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Table 5 – Summary of academic contributions (continued)

<table>
<thead>
<tr>
<th>Creation of general new data and insights for policy support</th>
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<td>The following sets of indicative information were published:</td>
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<tr>
<td>• Size and timing of regional and national generation and grid network investments required to meet rising electricity demand in Africa.</td>
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<td>• Electricity exchange between countries in Africa in different scenarios and illustrating that a lower electricity demand can potentially enhance trade.</td>
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<tr>
<td>• An implicit cost-competitiveness comparison of energy resources across Africa and insights on project-specific impact on national grid systems. For instance, in the Grand Inga analysis Nigeria is not affected, as its demand is satisfied mainly through domestic gas-fired generation, solar PV and hydro.</td>
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<td>• Illustrating that storage options can offer benefits to conventional thermal generation in Cyprus, by reducing ramping of gas-fired CCGTs.</td>
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<tr>
<td>• Illustrating that a shift away from oil products to natural gas facilitates the achievement of EU targets on CO₂ emissions in the ETS sector by 2030.</td>
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<tr>
<td>• Estimates on annual electricity generation cost in Cyprus across scenarios.</td>
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<tr>
<th>Creation of specific insights with respect to RET deployment</th>
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<tr>
<td>• Insights regarding the viability of proposed large scale RET projects (e.g. Grand Inga) and implications of different (a) levels of trade, (b) electricity demand growth rates and (c) infrastructure development schedules.</td>
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<td>• Identifying national grid systems affected by the development of RET projects in other countries and subsequent trade of electricity.</td>
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<tr>
<td>• Identifying interconnector projects to unlock RET potential in Africa.</td>
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<tr>
<td>• Cost-competitiveness of RET in an underdeveloped grid system (i.e. Africa) and an isolated fossil-fuel fired generation system (i.e. Cyprus). Timing and level of investments by technology in each region and country.</td>
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<tr>
<td>• Indicating benefits of a grid interconnector on RET deployment in Cyprus.</td>
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<tr>
<td>• Information on level of storage required to increase RET shares in Cyprus.</td>
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</table>

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<th>New ICT infrastructure</th>
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<tr>
<td>• The development of the open national-scale model for Africa creates an opportunity for capacity building for interested authorities on the continent.</td>
</tr>
<tr>
<td>• An open model of the entire energy system of Cyprus was developed and handed over to local stakeholders along with supporting training material.</td>
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</table>
4.2 Limitations and Future work

The models are set up in a way that enables sensitivity analysis to be conducted on a number of key assumptions. Multidimensional scenario discovery can be used to identify the areas in which the model, and hence the system, is most sensitive to. The effect of changing climate on RET deployment is one aspect that merits such a scenario analysis, particularly in the case of hydropower projects. Furthermore, the use of open modelling platforms allows academics or any other stakeholders to question the input data and assumptions and even revising them. By keeping the entire process transparent, the trust of policy makers towards the model outputs can be gained.

One aspect that is only investigated explicitly in the Cyprus case is that of storage options. Since Cyprus is an isolated grid system, pumped hydro and Li-ion batteries emerge as important enablers of RET. The vast distances between settlements in certain areas of Africa imply that energy islands will likely exist as well. In such cases, electrical storage will be required, especially if variable RET will contribute to a significant share of the generation mix. A more detailed investigation of the role of storage is needed in the African case study and enhancements will be made in this regard in the specific national-scale Africa model.

Further improvements that are necessary in the African case relate to the temporal resolution adopted in the national scale model. A larger number of time-steps used can allow the identification of time periods during which trade of electricity is optimal between different countries. This is partly affected by the variation in seasonal availability of renewable energy sources. For instance, the rainy season can vary in different regions of the continent, affecting hydropower or solar electricity output accordingly. Similarly, daily variations in electricity demand and their effect on RET deployment can be assessed with an increased temporal resolution.

Future enhancements of the models can include explicit representation of demand-side options that can compete directly with investments on the

59 These include but are not limited to: discount rates, technology learning rates, fuel cost projections, final electricity demand projections.
supply-side. In this way, a visualization can be provided for additional energy efficiency measures at cost-optimal levels, beyond the measures foreseen by the utilized final electricity demands.

4.3 Impact of the thesis

An active collaboration was carried out with authorities from the Republic of Cyprus in the work that led to papers VI and VII. By building the country’s national energy system model in OSeMOSYS (part of the work is presented in Paper VII), Cyprus became the first national government in the EU to adopt the use of an open model. This comes in compliance with the EU communication on the use of Open Data\textsuperscript{60}.

The final version of the model developed for Cyprus, which encompasses the entire energy system, will guide the formulation of a revised National Energy Action Plan to be submitted to the European Commission by the end of 2017. In fact, based on direct results of the model, authorities will seek to attain permission for statistical transfer of RES targets from the transport sector to electricity supply and heating and cooling.

Insights from the national scale model of Africa were presented at a side event that took place during the COP21 in Paris, informing participants on the outlook of the electricity supply sector in Africa. Since, electricity demand in Africa is rapidly increasing, the chosen suite of generation technologies to be deployed has a significant impact on the climate agenda. The national scale model of Africa has also been used to provide input to the first open source geospatial electrification analysis toolkit [140]. This toolkit is valuable in assessing the cost-optimal mix between grid-supplied electricity, mini-grid and off-grid generation options.

References


[140] D. Mentis et al., “Lighting the World: The first global application of an open source, spatial electrification tool (ONSSET), with a focus on Sub-Saharan Africa,” Forthcoming.
Appendix A – Assumptions in the final Cyprus analysis

Limited changes were done in terms of model structure and input assumptions to the ones adopted in Paper VII. Specifically, storage options were only allowed to provide as much operational reserve as the equivalent energy stored in the batteries for each respective year. Additional, different final electricity demand and fuel price assumptions were adopted. These are shown in the tables below.

Table A.1 - Final Electricity Demand (GWh) – provided by Dr. Zachariades (Cyprus University of Technology).

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Table A.2 - Fuel price and CO₂ emissions cost in the generation sector.

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<tbody>
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<td>Brent crude $/bbl</td>
<td>46.55</td>
<td>47.58</td>
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<td>51.20</td>
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<td>56.80</td>
<td>59.80</td>
<td>62.90</td>
<td>66.30</td>
<td>67.04</td>
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<tr>
<td>CO₂ $/tCO₂</td>
<td>12.10</td>
<td>13.20</td>
<td>15.40</td>
<td>16.50</td>
<td>17.60</td>
<td>18.70</td>
<td>19.80</td>
<td>20.90</td>
<td>22.00</td>
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<tr>
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<td>6.73</td>
<td>6.88</td>
<td>7.03</td>
<td>7.40</td>
<td>7.79</td>
<td>8.20</td>
<td>8.63</td>
<td>9.08</td>
<td>9.57</td>
<td>9.67</td>
<td>9.78</td>
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<tr>
<td>Diesel $/GJ</td>
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<td>12.22</td>
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<td>9.69</td>
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<td>10.88</td>
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<td>CO₂ $/tCO₂</td>
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<td>15.37</td>
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