Paper ID APEN-MIT-2020_336
Applied Energy Symposium: MIT A+B
August 12-14, 2020 • Cambridge, USA

Assessing the role of variable renewables in energy transition: methodologies and tools

Ettore Bompard, Alessandro Ciocia, Daniele Grosso, Tao Huang*, Filippo Spertino,
Department of Energy
Politecnico di Torino
Turin, Italy
{name.surname}@polito.it

Audun Botterud, Mehdi Jafari
Laboratory for Information and Decision Systems
Massachusetts Institute of Technology
Cambridge, USA
audunb@mit.edu, jafari@mit.edu

Abstract— Due to the environmental impacts brought by current energy schemes, the energy transition, a new paradigm-shift from fossil fuels to renewable energy, has been widely accepted and is being realized through collective international and local efforts. Electricity, as the most direct and effective use of renewable energy sources (RES), plays a key role in the energy transition. In this paper, we first discuss a viable pathway to energy transition through the electricity triangle, highlighting the role of RES in electricity generation. Further, we propose methodologies for the planning of wind and solar PV, as well as how to address their uncertainty in generation expansion problems. Finally, by using a web-based tool, "RES-PLAT"[1], we demonstrate the scheme in a case study of the North Africa, which evaluates the impacts and benefits of a large-scale RES expansion.

Keywords—energy transition, RES planning, res-plat, generation expansion, uncertainty, North Africa

I. INTRODUCTION

The energy transition, which is characterized by the shifting from fossil-based energy and economic schemes towards renewable-based ones, is gaining momentum at the global scale. Actions have been taken at different paces and segments in various countries to achieve the energy transition in order to ensure a sustainable and secure future energy system and economy. Electricity, as the most direct and effective use of RES, stands at the center of the energy transition. The impact of decisions related to the energy transition needs to be assessed holistically. This can be done through the so-called electricity triangle, i.e., electricity generation from RES, the transmission and distribution of energy in the form of electricity, and electrification at the final energy use [1].

In the electricity triangle, cost-effective integration of RES into the electricity system is vital to guarantee energy security, affordability, as well as sustainability. Therefore, in this paper, we propose methods for the planning of RES (Wind and Solar PV), considering the site-related weather and roughness information. To reduce the efforts in searching for suitable site locations for RES generation, we propose a set of pre-screening criteria. Further, we show how to take into account interannual variability and uncertainty of RES in the system planning and operation problem using multiple years of RES data, and find optimal solutions for the generation system configuration which is robust over different weather years.

Regarding the RES planning method, hourly power profiles are calculated starting from weather data (irradiance, air temperature, and wind speed), and roughness of the installation site, and other decisive factors, such as thermal losses, and the efficiency of electronic converters. We also consider wind speed-power output correlations to compare different commercial turbine models and define the best wind turbine in each location. Finally, a comparison between production profiles and consumption profiles permits us to define the best portfolio of photovoltaic plants and wind turbines. As for the uncertainty of RES in the generation expansion, we argue that instead of relying on a single year of time series data, it is important to optimize the system for multiple years of renewable and load data to ensure robust operation of the system across different weather years.

Finally, we apply the models implemented in the "RES-PLAT" developed at the EST@ Energy Center – PoliTO Lab to North Africa to quantitatively evaluate the RES exploitation potential and the exporting possibility to Europe based on a set of scenarios.

II. THE ROLE OF ELECTRICITY IN THE ENERGY TRANSITION

A. Energy Transition

The crucial role of energy in society is a well-received concept, and its availability is an important indicator of the level of welfare of nations and social communities, from survival to prosperity. After centuries of development, the current world energy system depends heavily on fossil fuel and fosters several issues that need to be addressed.

GHG emission: Energy accounts for 2/3 of global greenhouse gas (GHG) emissions [2]. In 2017 fossil fuels accounted for 81.3% of the global Total Primary Energy Supply (TPES), which produced 32.8 Gt CO_2 emissions - and increase of 60% w.r.t. 1990. The US, EU, Russia, China, India, and Japan accounted for about 67% of the overall CO_2 emissions [3]. Consequently, climate change becomes increasingly evitable and concerning. For example, the global land and ocean surface temperature increased 0.85°C

[1] https://res-plat.est.polito.it

over the period 1880-2012, the Arctic sea-ice extent reduced 3.5÷4.1% per decade over the period 1979-2012, and the global mean sea level increased 0.19 m over the period 1901-2010 [4]. The strong increase in the anthropogenic emissions w.r.t. the pre-industrial levels has led to atmospheric concentrations of CO_2, CH_4, and N_2O that have not been reached in the last 800,000 years [4]. Through international negotiations, the Paris agreement aims to make sure the increase of the global average temperature will be held well below 2°C above pre-industrial levels [5].

Air pollution: The use of energy commodities is responsible for the majority of pollutant emissions, according to [6], more than 99% of SO2 and NOX, 90% of CO, 80% of PM2.5, and 60% of VOC are emitted from the use of energy commodities. These have a large and negative impact on the wellbeing of people around the world. The estimation from IEA said that in 2012, the world deaths that can be attributed to air pollution were 7.3 million and the accumulative years of life lost were about 262 million-years [6].

Depletion of fossil fuels: The fossil resources are not sustainable. At the current consumption rate and the already known reserves, the fossil fuels will be depleted within around a century, more specifically, gas and oil will be gone in about 50 years, and coal will be depleted in 130 years, according to [7].

These factors are critical drivers for the energy transition. The energy transition is the mid/long-term transition of energy systems towards decarbonization, i.e., with a shift of the energy mix from fossil fuels to renewable energy sources (hydro, solar, wind, geothermal, biomass, tidal). Even if nuclear could be an option for the baseload, and it is carbon-free, its share in the electricity generation is expected to remain limited (6.1-11.7% by 2050, according to [8]).

B. *Electricity triangle*

RES have a huge theoretical resources potential, in principle being able to cover the global energy needs by a wide margin. According to the survey in [9], the long-term potential of electricity generated from RES are between 1340–14,780 EJ/y for PV, 250–10,790 EJ/y for concentrated solar power (CSP), 350–1800 EJ/y for onshore wind, 1000–3050 EJ/y for the overall wind (both onshore and offshore), 118–1109 EJ/y for geothermal, and 53 EJ/y for hydro. Considering the global TPES of 585 EJ in 2017, it can be satisfied by the solar flux reaching the Earth in less than 2 h [10]. Therefore, if we can tap into the huge availability of these resources, electricity can be generated entirely from RES, achieving the carbon-free economy targeted by the energy transition.

However, converting RES to electricity alone is not enough. It only solves the problem on the electricity production side. Two additional elements are needed to implement the electricity-based energy transition, i.e., the transmission of electricity as an energy vector and electrification of final energy. The triangle formed by these 3 fundamental elements for energy transition is called the electricity triangle.

- Power generation directly from renewable energy sources, mainly wind and solar, replacing generation from fossil fuels;
- Use electricity as an energy carrier to transmit and distribute energy with transmission and distribution infrastructures, taking advantage of high efficiency, low losses, and instantaneous transport.
- Electrification of energy end-uses to provide needed services with higher efficiency than other energy commodities.

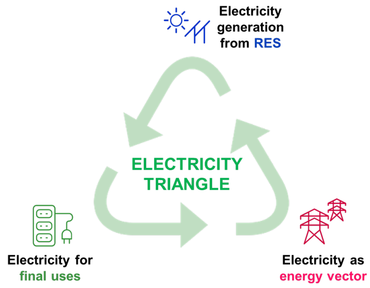

Fig. 1. ELECTRICITY TRIANGLE

Moreover, due to RES variability, energy storage systems are key elements to keep the secure operation of the electricity systems. This includes technologies to ensure power quality (fast release of power in a short time), like electrochemical storages, super-capacitors, electro-mechanical systems; technologies providing frequency regulation services (e.g., “cold” and “warm” electrochemical storages for Frequency Containment Reserve, flow batteries and compressed air energy storage for Frequency Restoration Reserve); and long-term storage (pump-hydro plants and new approaches like Power-to-X).

In addition, electricity from RES has to communicate with other commodities, at least in the short to mid-term. The cross-vector interplays among electricity, hydrogen, and gas are crucial. For example, the implementation of Power-to-Gas technologies for long-term storage, optimally exploiting the excess of electricity from RES and avoiding curtailments, etc., need well-designed interoperable multi-energy systems.

Considering the complexity of the energy transition, the RES deployment needs planning capable of matching technical aspects with sustainability issues and the economic feasibility of the investments. Therefore, science-based tools for decision-making support through comprehensive analyses and impact assessment are indeed needed.

III. ASSESSING THE RES POTENTIAL

PV generators and wind turbines are today the most used renewable energy technologies in the world due to several reasons. First, the use of solar and wind energy does not present issues related to scarcity in many locations. In addition, from a financial point of view, the return on investment of PV and wind power is high and, above all, increasing (unlike most of the fossil fuels). Another key aspect is the huge availability of raw materials (like silicon) in the Earth’s crust. Finally, in particular for solar panels, the structure of the devices is compact, and the thermal load is so low that maintenance is not an issue. For these reasons, the levelized cost of solar energy is lower with respect to other technologies in many countries. Therefore, in this section, we introduce methodologies for planning of solar PV and wind, as well as rules for site selection.

A. Modeling of solar photovoltaic production

The electrical performance of Photovoltaic (PV) generators can be accurately described by an equivalent model with lumped parameters. In the literature, the most used is the Single Diode Model (SDM), which is characterized by five parameters (Fig. 2): the photo-generated current I_{ph}, the saturation current I_0, the series resistance R_s, the shunt resistance $R_{sh,}$ and the p-n junction quality factor n [11]. In particular, the first current is the production of the solar cell, while the second term is a source of loss, reducing the solar cell output. R_s is due to the front electrical contacts of the cell, while R_{sh} is due to the leakage currents flowing through the lateral surfaces of the cell.

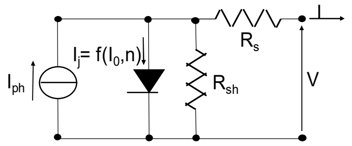

Fig. 2. EQUIVALENT CIRCUIT OF A PV CELL.

Four of the five parameters of SDM are generally considered constant, while the fifth is I_{ph} that is proportional to irradiance. Recently, researchers are working to increase the accuracy of the model by considering a dependence on weather conditions of all the parameters. As shown in the equations from (1) to (4), I_{ph} and R_{sh} are, generally, assumed proportional to irradiance; I_0 has a cubic dependence with temperature; R_s is mainly proportional to temperature; n has a weak linear dependence with irradiance, and temperature. The optimization of the coefficients in the semiempirical formulas is currently a hot topic in photovoltaic research [12].

$$I_0 = \boldsymbol{b} \cdot \left({}^{T}/_{T_{STC}} \right)^3 \cdot exp^{\left(\frac{1}{k} \left(\frac{E_{g,STC}}{T_{STC}} - \frac{E_g(T)}{T} \right) \right)} \tag{1}$$

$$n = \boldsymbol{c} \cdot G + \boldsymbol{d} \cdot T \tag{2}$$

$$R_s = \boldsymbol{e} \cdot \left({}^{T}/_{T_{STC}} \right) \cdot \left[1 + \boldsymbol{f} \cdot \ln \left({}^{G}/_{G_{STC}} \right) \right] \tag{3}$$

$$R_{sh} = \boldsymbol{g} \cdot \left({}^{G_{STC}}/_{G} \right) \tag{4}$$

In order to obtain a simple but accurate model for planning purposes, the SDM, applied to clear sky days in the four seasons, is interpolated by a straightforward model including different types of losses in the energy conversion. Thus, from the current-voltage curve, it is profitable to adjust a simpler model of PV power proportional to irradiance G, by PV efficiency η_{PV}, that has a quasi-constant dependence on irradiance:

$$\eta_{PV}(G) = \eta_{STC} \cdot \frac{G - G_0}{G} \cdot \Pi_\eta \tag{5}$$

with
$$\Pi_\eta = \eta_{th} \cdot (1 - \xi_{mix}) \cdot \eta_{DC/AC} \tag{6}$$

Π_η is an equivalent efficiency calculated as the product of the thermal efficiency (η_{th}), the non–linear efficiency in the DC/AC conversion ($\eta_{DC/AC}$), and the other sources of losses (1 - ξ_{mix}). Regarding η_{STC}, the most important worldwide manufacturers sell crystalline silicon modules with a typical efficiency up to ≈21% [13][14]. Fig. 3 shows the nonlinear dependence of the PV generator efficiency as a function of irradiance and temperature. In particular, the PV efficiency is quite constant for high irradiance values (G>600 W/m^2), while it strongly decreases in the case of G<200 W/m^2.

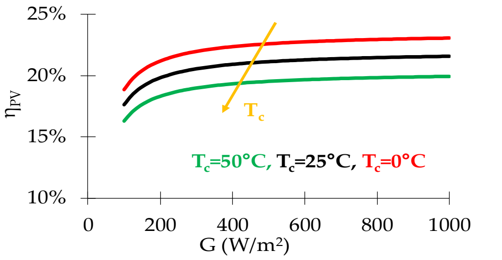

Fig. 3. PV EFFICIENCY AS FUNCTION OF IRRADIANCE AND TEMPERATURE.

B. Modeling of wind turbine production

The calculation of wind turbine production requires the wind speed distribution and the "wind speed-to-power output" relationship (manufacturer's power curve of the turbine). Regarding the wind speed distribution, wind speed data are transferred to the height of the turbine hub by the following equation, depending on terrain roughness:

$$u_W(z) = u_{ref} \cdot \frac{ln\left({}^{z}/_{z_0} \right)}{ln\left({}^{z_{ref}}/_{z_0} \right)} \tag{7}$$

where u_w is the wind speed (m/s) at the height z of the hub (m), u_{ref} is the wind speed (m/s) measured at the height of the weather station z_{ref}, and z_0 is the roughness length. Roughness is low in the case of water, and it is high for uneven terrain, such as mountains or cities with tall buildings and skyscrapers [15].

Regarding the "wind speed-power output" relationship, for the correct planning of wind farms, the best turbine should be selected for the specific locations. The selection is performed comparing the performance of different commercial wind turbines (WTs); for each turbine, the global efficiency of a wind turbine is calculated as the ratio between the electric power output and the aerodynamic wind power:

$$\eta_{WT}^{glob} = \frac{P_{el}^{WT}}{0.5 \cdot \rho_{air} \cdot A \cdot u_W^3} \tag{8}$$

where u_W (m/s) is the wind speed, at the height z of the rotor hub, passing through the swept area; A (m^2) is the swept area of the three-blade disk (perpendicular to the wind speed), a function of the blade length.

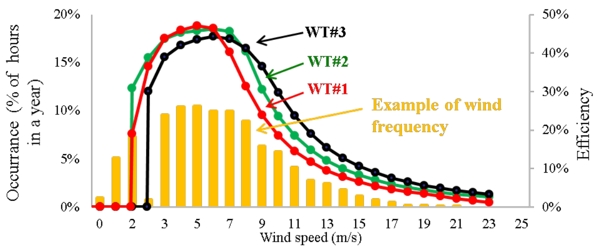

Fig. 4. COMPARISON BETWEEN THREE WTS WITH DIFFERENT CHARACTERISTICS

Fig. 4 illustrates the wind speed distribution for a good site in North Africa in which the efficiency curves of three different turbines are compared. In this site, the best performaning turbine (WT#1) has the largest rotor and the tallest hub height: it permits to extract the highest energy at low wind speed. Turbine (WT#2) has average performance with the same rotor as (WT#1) and lower hub height. WT#3 is a long-life turbine designed for higher wind classes; thus, it has the lowest performance and less maintenance than the others.

C. *Criteria for the selection of suitable sites for RES*

A correct procedure for the planning of RES requires criteria that can be divided into two macro-categories, closely related to each other: technical feasibility and cost-effectiveness. In fact, the installation sites should be chosen in order to ensure not only the feasibility of the installation from a technical perspective but also to avoid an increase in the installation or operation and maintenance costs. For example, referring to PV plants and wind turbines, they should not be installed in case of:

- too high slope of the terrain (<10% for wind turbines);
- excessive height of the sites: extreme weather conditions can damage the WT blade and drive train materials. The height limit depends on the climate and geographical location in a country/region, and on the characteristics of the turbines. As an example, one of the most important manufacturers of wind turbines in the world suggests to consider a reference limit in the range 1000—1500 m for a 2MW turbines [16]. Above this limit, special considerations must be taken regarding, for example, snow and icing, that can affect the performance of wuind turbines and HV installations.
- special weather conditions: e.g. in desert areas, sandstorms could damage PV glass and mechanical parts of wind turbines, strongly reducing their lifetime;
- proximity to special building and infrastructures (e.g. airports or military facilities);
- other factors such as terrain morphology not suitable for this kind of installations.

IV. MANAGING UNCERTAINTY FROM RES

In the evaluation of the role of RES in the transition towards decarbonized electricity systems, generation potential from the RES such as solar and wind are used in optimization models for the planning and operation of the electricity system. However, most of the capacity expansion studies with focus on RES integration rely on single year RES data. Such analyses, although they provide optimal solutions for the studied year's data, are not comprehensive due to spatio-temporal variations of RES over time.

Interannual variability of RES can substantially change the optimal generation portfolio and its operation in different years. Relying on single year data of RES for capacity expansion decisions can result in flexibility, reliability and financial issues for the system. A system that is optimized for one year of RES may face capacity inadequacy in other years, which may cause load curtailments and lower reliability. Higher load curtaiments also lead to high operational system costs, which could be prevented by appropriately accounting for the RES variability. In addition, insufficient investment in flexibility resources such as energy storage may increase RES curtailment leading to waste of clean energy resources.

Therefore, key challenges in high-renewable power systems planning and operation problems include: 1) consideriation of high-resolution RES generation availability data for multiple years, 2) accounting for RES forecast uncertainty in operating reserve requirements, 3) adequately representing flexibility characteristics of generation, demand, and energy storage. To address these challenges, the objective function of a stochastic generation expansion problem can be expressed as in (9) [17].

$$\min \mathrm{C} = \sum_g \left(C_g{}^{Inv.} \times A_g \times \delta_g{}^{Inv.} + C_g{}^{FixOM} \times \Delta_g \right) + \sum_y \left[W_y \left(\sum_t \left\{ \begin{array}{c} \sum_g \left(C_g{}^{VarOM} + C_g^{Fuel} \right) \times \phi_{g,y,t} + \\ \left(C_s^{VarOM} \times \phi_{s,y,t} \right) + \left(C^{ENS} \times \gamma_{y,t}{}^{e} \right) + \left(C^{R} \times \gamma_{y,t}{}^{r} \right) \end{array} \right\} \right) \right] \tag{9}$$

The objective is to minimize investment and operation costs of the system considering multi-year variations of the RES and load. $C_g{}^{Inv.}$ is the investment cost of generation technology g (\$/MW), A_g is its annuity factor and $\delta_g{}^{Inv.}$ is its invested capacity (MW). $C_g{}^{FixOM}$ is the annual fixed operation and maintenance (O&M) cost of generation technology g in \$/MW-yr. Δ_g is the total installed capacity of g in the target year which is the sum of existing capacity $\delta_g{}^{A}$ and $\delta_g{}^{Inv.}$ minus retired capacity $\delta_g{}^{Ret.}$. W_y is the weight used to normalize the costs to an annual value for year y. $C_g{}^{VarOM}$ and C_g^{Fuel} are the variable O&M and fuel costs of generation technology g and ϕ_g is the energy injected to the system by g. C_s^{VarOM} and $\phi_{s,t}$ are the variable O&M cost and charged/discharged energy to/from the ESS. C^{ENS} and C^{R} are the energy not served (demand curtailment) and unmet reserves penalties, $\gamma_t{}^{e}$ and $\gamma_t{}^{r}$ are ENS and unmet reserves (MWh) at time t. This objective function is subject to different technology specific and system level constaints, e.g.:

- Generation units' investment constraints
- Thermal, RES and storage units' operational constraints
- Unit commitment constraints
- Reserves and regulations constraints on individual units
- CO_2 emissions constraints
- Hourly energy balance constraints
- Total reserves requirements

This generic formulation can be used to evaluate the role of RES interannual variability and uncertainty on the optimal system configurations and propose robust solutions for the generation portfolio and its operation based on multiple years of measured or projected RES data in different locations. The RES data for different times and locations can be obtained from tools such as RES-PLAT and used as an input for the generation capacity expansion planning.

V. CASE STUDY: RES EXPLOITATION IN NORTH AFRICA

This section reports the results of an assessment of the energy productivity from RES in North African countries (namely, Morocco, Algeria, Tunisia, Libya, and Egypt). The analysis considers the possible generated surplus, able to allow for an energy dialogue and exchange based on RES between the southern and the northern shore of the Mediterranean sea (i.e., with European countries). A quantitative evaluation of the possibility of RES exploitation in terms of annual energy production and hourly power injection is provided through a model originally developed at the EST@ Energy Center – PoliTO Lab. The focus of the analysis has been on WTs and solar PV, which – among the different renewable sources – seem to be the most promising options currently, although concentrated solar, wave, and geothermal energy might play a role in the future [18].

A. *Productivity scenarios*

The energy production profiles from PV and wind power installations are obtained by using the ENEMED ENERGEO/RES analysis platform, developed at EST@ Energy Center – PoliTO Lab [19] which implements the methodological approach explained in Section III and coupled with an interactive georeferred representation through GIS maps. It allows performing multiple simulations and comparing renewable production of specific sites, areas, and countries. In the present case, several locations of the North African countries were selected based on the criteria described in Section III. The database provides hourly values of weather data (irradiance, air temperature, and wind speed) from 2006 to 2016. Regarding future production, three scenarios are considered:

- *RES low:* power generation from RES is used only for fulfilling the electricity demand of North Africa;
- *RES medium*: besides the fulfillment of North Africa electricity needs, a surplus is available for trans-Mediterranean exchanges;
- *RES high*: significant electricity surplus is available for exchanges between Europe and Africa.

Table I shows the estimation of PV and wind power plant installations until 2040 in the three different scenarios described above. In particular, regarding Egypt, in the *RES low* scenario, the installed total power of PV and WT ranges between 78 GW and 87 GW, in the *RES medium* is between 106 GW and 117 GW, while the maximum value (RES high) is in the range 245-270 GW. In all the scenarios, Egypt and Algeria show the highest contribution, corresponding to more than 70% of the overall estimated installed power of North Africa.

TABLE I. ESTIMATED INSTALLED POWER OF PHOTOVOLTAIC PLANTS AND WIND TURBINES (THE YEAR 2040)

Nominal power of PV and wind systems (GW)			
Area	***RES low***	***RES medium***	***RES high***
Algeria	49–54	71–78	164–181
Egypt	78–87	106–117	245–270
Libya	12–13	23–26	55–61
Morocco	22–25	32–35	56–61
Tunisia	10–11	17–19	40–44
TOTAL	173–191	251–277	561–620

B. *Demand scenarios*

Currently (2017 data), the electricity generation in the five North African countries is equal to about 354.4 TWh. The average level of electrification is 18.1%. In particular, the electricity production of Egypt (188.2 TWh) accounts for more than 50% of the total [20].

Regarding the projections of the Total Final Energy Consumption (TFC) and of the related electrification rate by 2040, two scenarios are considered:

- *Reference scenario:* the TFC and the electricity consumption are projected to 2040 on the basis of the best fit of historical data. This leads to an overall increase of the TFC equal to 37.1% over the period 2020-2040 for the whole area, corresponding to an average annual growth rate of 1.4%. For the single countries, the percentage variation between 2020 and 2040 is in the range of 25.4% (for Algeria) to 40.5% (for Tunisia). Libya is the only exception: in this country, the forecasted increase in TFC is equal to 91.4%, due to the strong reduction in TFC during recent years caused by political instabilities and to the fact that, when this geopolitical situation will be overcome, the consumption trend would be realigned with the previous trend.
- *High Electrification scenario:* it has the same projection approach as the Reference scenario for TFC, while the electrification rate in all the North African countries is assumed to reach 50% by 2040. According to this, the electricity consumption in 2040 has been calculated as half of the projected TFC in the same year, assuming a linear growth between 2017 and 2040.

Table II summarizes the scenario projections in terms of the TFC and electrification ratio.

TABLE II. SCENARIO PROJECTION UP TO 2040 FOR NORTH AFRICAN COUNTRIES

Scenario projections				
Scenario	**Country**		**2020**	**2040**
Scenario 1 - Reference	Algeria	TFC [PJ]	1659.4	2014.0
		Electrification [%]	14.0	21.0
	Egypt	TFC [PJ]	2673.2	3508.3
		Electrification [%]	22.5	22.2
	Libya	TFC [PJ]	414.6	709.0
		Electr [%]	14.0	15.0
	Morocco	TFC [PJ]	700.9	882.9
		Electr [%]	19.1	28.3
	Tunisia	TFC [PJ]	368.4	491.6
		Electrification [%]	16.7	17.1
Scenario 2 - High electrification	Algeria	TFC [PJ]	1659.4	2014.0
		Electrification [%]	18.6	50.0
	Egypt	TFC [PJ]	2673.2	3508.3
		Electrification [%]	27.2	50.0
	Libya	TFC [PJ]	414.6	709.0
		Electrification [%]	21.8	50.0
	Morocco	TFC [PJ]	700.9	882.9
		Electrification [%]	22.7	50.0
	Tunisia	TFC [PJ]	368.4	491.6
		Electrification [%]	22.4	50.0

C. *Overall scenarios*

Considering the production and consumption scenarios of the previous subsections, we buil three composite scenarios:

1)Scenario A: RES low + Reference
2)Scenario B: RES medium + Reference
3)Scenario C: RES high + High electrification

The main energy results of the three scenarios are summarized in Table III.

TABLE III. SCENARIOS PROJECTIONS IN 2040 FOR NORTH AFRICA

	Annual electrical energies [TWh]		
Scenario	**RES production**	**Load**	**Surplus**
A	456	456	0
B	661	456	205
C	1479	1056	423

In scenario “A”, the installed power of PV and WT is in the range 173-191 GW; these resources fully supply the yearly electric loads of the North Africa countries, corresponding to 456 TWh in the year 2040. In scenario “B” the higher installations (251–277 GW) permit to produce a considerable annual surplus for foreign countries (>200 TWh). It corresponds to 31% of the production of the entire North African region. From the point of view of the single countries, the ratio between surplus and production is higher in Libya and Tunisia, where the electrification rate is expected to grow less in the next twenty years. Finally, in the scenario "C" (RES high + High electrification), the installation of PV and wind system (561–620 GW) totally supply the electric load (corresponding to an electrification rate of 50%) and provide about 420 TWh available for trade with foreign countries.

D. A Possible Electricity Trade Between Africa And Europe

The energy surplus defined in the considered scenarios requires an adequate development of infrastructures to transfer it to the other countries. Currently, ten electricity interconnections across the Mediterranean are in operation, with an overall capacity of about 5 GW. However, significant investments are already ongoing or planned: 3 new interconnectors are under construction, 9 are in the permitting phase, 1 is planned and 7 are under consideration, corresponding to a possible total increase up to ≈21 GW. The total investments for these infrastructures can be quantified to 21 billion € [21]. Despite the huge investments, simulation results demonstrate the bottleneck effect of the transmission lines between North Africa and Europe. Considering a reasonable interconnection capacity of 12.5 GW, corresponding to the capacity of the lines that could link Europe with the five considered North African countries in 2040, the import energy flow in Europe is a fraction of the available energy surplus generated in North Africa. Table IV shows that in Scenario B only 44.0% and in Scenario C only 21.2% of the total available annual electricity surplus from North Africa is exported to Europe, mainly due to the limited overall capacity of the hypothesized infrastructures. In addition, this import is only 2.4% of the total European electricity demand (3706 TWh/year) in both scenarios. Nevertheless, from a market perspective, the import of electricity from RES could lead to a reduction in European electricity prices, thus resulting in economic savings.

TABLE IV. ELECTRICITY IMPORT FROM NORTH AFRICA BY SCENARIOS IN 2040

[TWh/y]	Annual electrical energies [TWh]		
Scenario	**A**	**B**	**C**
Available surplus	0	205	423
Maximum importable flow	110.2	110.2	110.2
Import from North Africa	0	90.3	89.5

VI. CONCLUSIONS

Electricity, as the most direct and effective use of RES, stands at the center of the energy transition. However, RES by itself is not the full solution; it should be fit together with the development of transmission infrastructure and electrification of the final uses. The energy transition is a multi-dimensional complex problem involving technical, economic/financial, environmental, geopolitical, and social aspects; thus, science-based supporting methods and tools are needed for assessing the impacts in a holistic way.

The RES planning needs to consider various information such as geomatic data, technical features, etc., for allowing the definition, implementation, and comparison of alternative scenarios, in order to identify the best solutions. The developed tools have to provide customized answers to the instances of several stakeholders from institutional and regulatory bodies, to energy companies, financial investors, etc., integrating different possible impact analyses in a multi-layer perspective.

This paper briefly summarized the models suitable for planning RES and managing their uncertainty in the generation expansion. The case study on the RES exploitation in north Africa, using the prototype web-based platform "RES-PLAT" at EST@ Energy Center – PoliTO lab, shows that the studied north African countries can easily fulfill the internal electricity demand at the hourly level, even in case of high electrification rates, making possible also trade with Europe. However, the investments in infrastructures are crucial for building an effective energy dialogue and exchange based on RES between Africa and Europe.

REFERENCES

[1] E. Bompard *et al.*, "An electricity triangle for energy transition: Application to Italy," *Appl. Energy*, 2020, doi: 10.1016/j.apenergy.2020.115525.

[2] International Energy Agency(IEA), "Climate change-The energy sector is central to efforts to combat climate change." https://www.iea.org/topics/climate-change (accessed May 06, 2020).

[3] International Energy Agency(IEA), "IEA Statistics." https://www.iea.org/statistics/.

[4] Intergovernmental Panel on Climate Change, *Climate Change 2014 Mitigation of Climate Change*. 2014.

[5] United Nations, "Summary of the Paris Agreement," *United Nations Framew. Conv. Clim. Chang.*, 2015.

[6] R. Priddle, "World Energy Outlook - Special Report Energy and Air Pollution," *World Energy Outlook - Spec. Rep.*, 2016, doi: 10.1021/ac00256a010.

[7] BPSTATS, "BP Statistical Review of World Energy Statistical Review of World, 68th edition," 2019.

[8] International Energy Agency(IEA), "World Energy Outlook," 2017.

[9] Y. Y. Deng *et al.*, "Quantifying a realistic, worldwide wind and solar electricity supply," *Glob. Environ. Chang.*, 2015, doi: 10.1016/j.gloenvcha.2015.01.005.

[10] E. Bompard, D. Grosso, T. Huang, F. Profumo, X. Lei, and D. Li, "World decarbonization through global electricity interconnections," *Energies*. 2018, doi: 10.3390/en11071746.

[11] A. Ciocia, P. Di Leo, S. Fichera, F. Giordano, G. Malgaroli, and F. Spertino, "A Novel Procedure to Adjust the Equivalent Circuit Parameters of Photovoltaic Modules under Shading," 2020, doi: 10.1109/speedam48782.2020.9161878.

[12] F. Spertino, S. Fichera, A. Ciocia, G. Malgaroli, P. Di Leo, and A. Ratclif, "Toward the complete self-sufficiency of an NZEBS microgrid by photovoltaic generators and heat pumps: Methods and applications," *IEEE Trans. Ind. Appl.*, 2019, doi: 10.1109/TIA.2019.2914418.

[13] Jinko Solar, "Modules datasheets." https://www.jinkosolar.com/en/site/tigerpro (accessed May 10, 2020).

[14] Trina Solar, "Modules datasheets." https://www.trinasolar.com/en-glb/product/utility (accessed May 10, 2020).

[15] Danish wind industry association, "Danish wind industry association." http://drømstørre.dk/wp-content/wind/miller/windpower web/en/stat/unitsw.htm#roughness (accessed Sep. 04, 2020).

[16] VESTAS, "Turbine datasheet." http://ventderaison.eu/gembloux/eie_ABO-WIND/Annexes/Annexe_N_1_Courbe_acoustique_V90.pdf (accessed Aug. 10, 2020).

[17] M. Jafari, M. Korpås, and A. Botterud, "Power system decarbonization: Impacts of energy storage duration and interannual renewables variability," *Renew. Energy*, 2020, doi: 10.1016/j.renene.2020.04.144.

[18] M. M. P. Boccardo, E. Bompard, S. Corgnati, D. Grosso, A. Ciocia, F. Spertino, G. Fulli, "Res exploitation in the Southern Mediterranean area: a perspective analysis at 2040," in *ENEMED, Med & Italian Energy Report*, 2020.

[19] "RES-Plat." https://res-plat.est.polito.it (accessed May 10, 2020).

[20] International Energy Agency (IEA), "World Energy Outlook 2019 – Analysis - IEA," *World Energy Outlook 2019*, 2019. .

[21] F. P. E. Arco, E. Bompard, C. Mosca, "Electricity based energy corridors connecting North and South shores of the Mediterranean," in *ENEMED, Med & Italian Energy Report*, 2020.