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The Feasibility of Small Modular Reactors (SMRs) in the Energy Mix of Saudi Arabia

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Abstract – *This paper discusses the technology and usage of SMR technology in the Kingdom of Saudi Arabia (KSA). Implementing such technology is helpful and can facilitate meeting the 2030 vision, which states net zero carbon emissions by 2060. SMRs with around 300 MWe contain advanced passive safety systems to reduce and eliminate the risk of accidental events. With their small size compared to large reactors, SMRs can be multi-unit to increase the power and reduce the cost. Also, Saudi is the largest producer of desalinated water and diesel generators used as a power source. Therefore, using SMR rather than diesel generators can reduce costs and greenhouse gas emissions. In Saudi Arabia, SMRs can be used as the primary source of electricity production for far-distanced areas, for example, or as an addition to existing plants. One unit of SMR can generate electricity for 0.93% of the population and produce 0.78% of the total energy produced in Saudi. Furthermore, beside adding value by producing hydrogen during non-peak hours, SMRs can integrate with renewable sources to compensate for the drawbacks since the vision states that renewables and natural gas will reach 50% of the energy mix in 2030.*

Keywords: Nuclear Energy; SMRs; SMART; Vision 2030; Sustainability; Electricity production; Desalination; Hydrogen Production; Renewables

I. Introduction

Nuclear energy (NE) is essential to establish a powerful carbon-free supply. NE can substitute power sources that emit CO2, such as oil and coal since the emissions produced by these sources are increasing daily with the increase of population worldwide. While NE, a very clean energy source, contains almost no air pollution content while operating. Furthermore, NE is a more reliable power source due to the high-capacity factor compared to natural gas, wind, and solar, as seen in Fig.1, and also due to less maintenance required and a more extended refueling period.

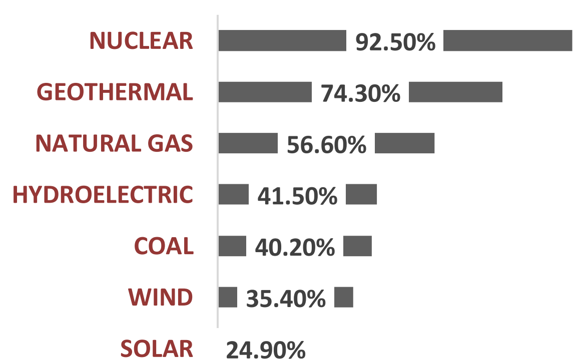

Fig. 1. Capacity factor by energy source – 2020 [1]

Although nuclear power is safe, a few events have been encountered previously. The significant events of the three known accidents related to nuclear power are, the Three Mile Island, Chernobyl, and more recently, Fukushima, accelerated the process of enhancing, improving nuclear technology and safety. For example, improving and implementing more advanced safety systems with redundancy, diversity, and independence, reducing the construction time for building a nuclear reactor, and designing new innovative nuclear technologies that can provide more flexibility and safety for more applications as compared to large reactors.

For instance, Small Modular Reactors (SMRs) are smaller nuclear fission reactors with a unique design having an electrical power of around 300 MW_e and up to 1000 MW_{th}. With small footprints, SMRs have the potential to be built more quickly and safely in factories with less construction time and can fit in trucks and shipping containers. In addition, SMRs could reduce costs, even the start-up cost, by starting with a single unit and adding additional units incrementally if the load on the grid increases. Moreover, SMRs have the potential to decrease the risk of delays in the construction of the power plant and provide many distinguished technological advances due to the flexibility of modular construction compared to large nuclear power plants [2].

On the other hand, the Kingdom of Saudi Arabia (KSA) depends mainly on fossil fuels to produce electricity. As a result and seen in Fig. 2, the CO_2 emissions in 2020 were around 575 million tonnes. However, with Saudi Arabia's 2030 vision, a strategy framework that was introduced in April 2016 sought to diversify Saudi Arabia's economy and lessen its dependency on oil [3], the Kingdom will reach net zero carbon emissions by 2060. To fulfill this plan, a clean and sustainable power source in Saudi Arabia is required, and the Kingdom selected nuclear power along with other sources.

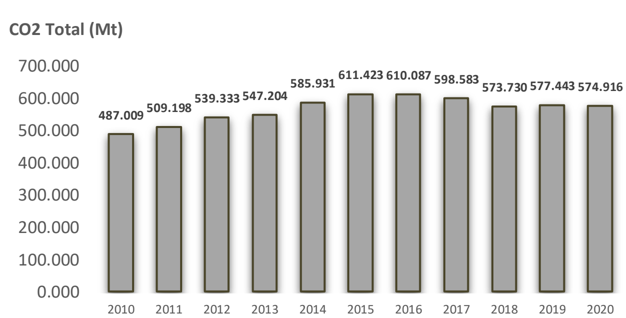

Fig. 2. CO_2 total emissions in Saudi [4]

Nuclear energy will be necessary for Saudi Arabia's development by departing from fossil fuels. SMRs, as part of it, will contribute considerably to the Kingdom for various applications. For instance, to develop desalination, to increase the power for existing power plants, to provide power for far-distanced places and for mega projects, such as Red Sea and NEOM [5], in the Kingdom with zero emissions.

II. SMR Concepts and Designs

SMR concepts use large reactor technologies with enhanced safety and higher operational performance. The concept behind SMRs varies depending on the type of the reactor, which could be water-cooled reactors like Pressurized-Water Reactor (PWR) or Advanced Modular Reactor (AMR) using generation IV technologies such as Lead-Cooled Fast Reactor (LFR), High-Temperature Gas Reactor (HTGR), Sodium-Cooled Fast Reactor (SFR), and Molten Salt Reactor (MSR).

Currently, many concepts of SMR designs exist (around 70 designs), and two are in operation, KLT-40S reactor by Russia for a floating nuclear power plant (NPP) and HTR-PM by China [6]. For both reactor designs, there are two reactors of each in operation.

Also, there are reactors under construction, like CAREM reactor and ACP100 reactor, and both use PWR type. Furthermore, some reactors are approved by the regulatory body such as Rolls-Royce SMR, and many conceptual designs exist, for example, the integral SMR and Aurora reactor.

III. Safety, Fuel Cycle and Waste Management

Safety is essential for any power plant, especially when discussing NPP. Through the years, NPPs have devoted enormous efforts to provide design solutions and innovative features that can improve safety. SMRs, as advanced reactors, have some innovative features that potentially will enhance safety. For most SMRs, one of the features is the passive cooling system, in which no electrical supplies are required to cool the reactor because electrical supplies are a significant issue during accidents. Nevertheless, the passive safety system allows the achievement of the cooling process using gravity and natural convection.

This passive system can reduce the cost and the maintenance required for the reactor [7].

The experience gained from current reactors and NPPs developed the reactors regarding the fuel cycle and waste management. The operation cycles extended between refueling in many SMR concepts compared to large reactors which refuel in around every 18 months [8]. Different examples of SMRs with long refueling cycles, such as KLT-40S, which has a refueling cycle of 30 to 36 months, are mentioned in [9]. Some ideas propose the usage of reprocessed fuel coming from LWRs to decrease the amount of spent fuel further.

Spent fuel from SMRs is dealt with similarly to that from large plants. For countries that have existed nuclear power programs, the process of dealing with spent fuel should be manageable due to the experience. On the other hand, countries that are new to nuclear energy need to think carefully about spent fuel management and set up a suitable infrastructure.

IV. SMR Status in Saudi Arabia

Fig.3 illustrates the status and activities of SMRs in Saudi Arabia, which are:

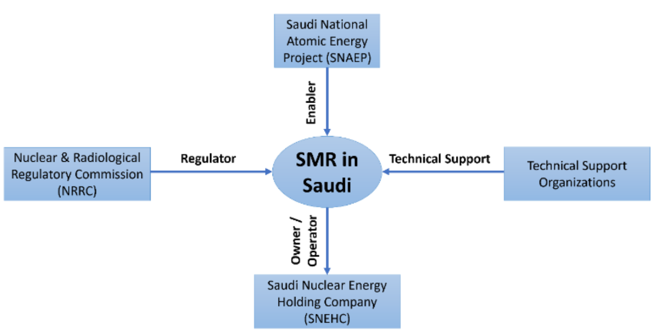

Fig. 3. The status of SMRs activities in Saudi Arabia

IV.A. Saudi National Atomic Energy Project (SNAEP)

The nuclear power program began in Saudi Arabia in 2010 through KACARE (King Abdullah City for Atomic and Renewable Energy). KACARE has been established to take responsibility for initiating oil alternative sources, nuclear energy, and radiation waste programs. Under Vision 2030, Saudi Arabia in July 2017 launched the Saudi National Atomic Energy Project (SNAEP) to introduce peaceful use of nuclear power into the country. The project focuses on three main pillars:

1- Large Nuclear Power Reactors
2- Small Modular Reactors
3- Uranium Exploration

Regarding large reactors, the objective is to construct the first two nuclear reactors with a capacity of 3.4 GW by 2032. According to authorities, the new facilities will be created with the most up-to-date technical standards and the strictest safety procedures [10]. Currently, NRRC is working with owner company on the site selection analysis and approval.

Regarding SMRs, Saudi Arabia has made a couple of agreements about adopting those technology in the country. Starting with the agreement signed in 2015 between South Korea and Saudi regarding specific SMR type designed by Korea Atomic Energy Research Institute (KAERI) SMART (System Integrated Modular Advanced Reactor) [11]. SMART is a passive safety system reactor that can produce up to 100 MW_e (330 MW_{th}) gross, refueling time estimated every three years. The reactor has a design life of around 60 years and three years of construction, which is low compared to large reactors. SMART has a distinct design from other reactors. The steam generators and the pressurizer are inside the vessel. The core is 2 m in length and consists of 57 fuel assemblies. The design allows some of the heat produced in the reactor to be used for water desalination. Furthermore, SMART is composed of four safety injection systems, two shutdown cooling systems, two emergency diesel generators, four residual heat removal systems, and a containment spray system [12].

Saudi Arabia in 2015 signed an agreement with Argentina to launch an Argentinian-designed modular reactor, a new type of SMR called (CAREM). The agreement came from the cooperation between Saudi company "Taqnia" with Argentinian one "INVAP" to establish a joint-venture company called "Invania," which is the responsible company for developing this PWR nuclear reactor [13]. The electrical capacity of CAREM is 27 MW_e, and the enrichment of the fuel is about 3.4% of Uranium-235. The refuelling process is annual. One of the advantages of this SMR is the natural circulation, meaning no requirements for pumps [14].

Also, two agreements were signed with China in 2016 and 2017 to initiate and facilitate building of a new small modular reactor called HTR-PM (High-Temperature Reactor Pebble-Bed Module). The first agreement was a memorandum of understanding to cooperate on constructing the reactor in Saudi Arabia. In addition, the second was signed in March 2017 to study the project's feasibility. The construction duration of the reactor is estimated to be five years. Currently, China started building the reactor in late 2012 in Shandong Province to be fully operational by the end of 2017 [15].

The SNAEP will be the main enabler of introducing the SMR in the country as one of the strategic options to be introduced.

IV.B. Nuclear & Radiological Regulatory Commission (NRRC)

In addition to those pillars, SNAEP will support the establishment of the regulatory body. In 13 March 2018 the Council of Ministers of Saudi Arabia approved the establishment of the Nuclear and Radiological Regulatory Commission (NRRC) as an independent regulatory body to oversee and supervise all the nuclear and radiation activities in the Kingdom. Since then, NRRC has introduced several polices, laws, technical regulations and others. All of which will help build safe and secure SMRs [16].

IV.C. Saudi Nuclear Energy Holding Company (SNEHC)

In February 2022, Saudi Arabia announced at the IAEA's Board of Governors the establishment of the Saudi Nuclear Energy Holding Company (SNEHC). SNEHC will be the owner and operator company of any nuclear power plants in the country and the empower agency for the SNEAP related activities. SNECHC will also focus on what type of SMRs to be introduced and what applications that is needed [17].

IV.D. Technical Support Organizations (TSOs)

Saudi Arabia is construction the first nuclear facility in at King Abdul-Aziz City for Science and Technology (KACST) which is the Saudi national lab. The Saudi Low Power Research Reactor (LPRR) is the first research reactor in Saudi and the Gulf region. It is an open pool type reactor, similar to several power reactors, with maximum power of 100 kW. The reactor specifications were designed and developed by King Abdulaziz City for Science and Technology with the participation of King Abdullah City for Atomic and Renewable Energy and international experts. The objectives of LPRR are to support the SNEAP activities and transfer the nuclear reactor technology in the Kingdom. Construction LPRR is designed and constructed with a strategic partnership of the Argentinian company INVAP. KACST also has the Nuclear Technology Institute (NTI). It has several nuclear and radiation infrastructure that can be used along with the human capacity as a technical support for the SMRs program in Saudi [18].

In addition to the national lab, KACARE as the leading organization to introduce the nuclear program in the country, has the capacity of providing the technical support for the program. Moreover, Saudi has several universities that have nuclear programs. Researchers at those universities can provide valuable research to support the program.

Furthermore, Saudi Arabia is an active member of the International Atomic Energy Agency (IAEA). The collaboration helps the Kingdom acquire efficient technical support by creating regulations and legal structures that will aid in the safe, secure, and transparent implementation of its nuclear energy plan [19].

V. Uses and Application of SMRs in Saudi Arabia

SMR reactors have several uses and applications some of the SMRs uses will help Saudi to reach its Vision. The energy demand has been increasing for the past two decades and is expected to grow even more with all the planned projects like Alula, Abha, and Neom. Hence, more supplies of energy are needed to compensate for this demand [20]. Also, this demand must be covered with as low as possible carbon emissions, as the Saudi Vision states.

V.A. Desalination

Saudi Arabia is the largest producer of desalinated water. It has the largest reverse osmosis water desalination plant, Rabigh Three (Guinness World Records) [21]. The Kingdom relies on desalinated water since there are no other sources of fresh water. As a result, this emphasizes the need for desalination plants. In the Kingdom, desalination plants use oil & gas as a source of energy, which are significant producers of greenhouse gas. Another source of energy that has fewer greenhouse gas emissions with a high technological level is nuclear energy.

Moreover, since conventional nuclear power plants occupy a large area, SMRs can solve this issue with much smaller size, advanced technology and safety, and the energy needed for desalination. Therefore, SMRs can be used in desalination plants in the Kingdom to provide the energy required for desalination and electricity. More than 150 reactors and years of experience have proven that integrated nuclear desalination plants are feasible. Examples are Kazakhstan, India, and Japan. Between 1973 and 1999, the BN-350 at Aktau, in Kazakhstan, produced 80,000 m^3/d of potable water and generated 135 MW_e of electricity.

According to the Saudi Water Conversion Corporation's (SWCC) annual report for 2019, Saudi Arabia is the largest producer of desalinated water worldwide. SWCC produced 1890 Mm^3 in 2019, an increase of 4% over the year before, accounting for 22% of global production. Saudi produced this quantity of water from 33 water desalination plants along the Red Sea and Arabic Gulf, and it was delivered to Saudi regions by a massive pipeline system with a length of 7,700 Km. Due to varied topography in different areas, there is an average rise in sea level of 900 m – 1100 m. The Corporation has constructed 63 pumping stations to provide water to every home in Saudi Arabia due to the length of this pipeline and the height above sea level [22].

In 2019, SWCC consumed 40 million MWh, or in terms of power (power calculations in average value)

$$P = \frac{40 \text{ x } 10^6 MW}{365 \text{ x } 24} = 4570 \text{ MW} \qquad (1)$$

(14.7% on the red sea and 85.3% on the Arabic Gulf). According to the report, one of the challenges SWCC faces is the low price of the electricity it produces when they sell it. The report also claims that one of SWCC's challenges is the company's high electricity production costs.

Using a diesel generator to generate 4600 MW of power has several drawbacks, including high CO_2 emissions and unstable costs. Since SWCC has 96 locations, some in remote areas, SMR and microreactors can be used instead of diesel generators in response to the demand for electricity in pumping stations. Additionally, this will assist SWCC in lowering its CO_2 emissions from 266.5 g CO_2/kWh to 16 g CO_2/kWh. Since SWCC generates about 48% of Saudi Arabia's electricity and meets the country's target of having net zero CO_2 emissions by 2060, this will aid in lowering CO_2 levels there. Also, in terms of cost, the average cost of producing 1 KWh by diesel generator can range from 0.80 $ – 5.00 $ per KW [23] due to fluctuating oil prices, while the cost of producing 1 KWh by NPP is 0.46 $ per KW [24].

V.B. Electricity Production

SMRs can produce up to 300 MW_e, and this considerable power can take responsibility for a small town or part of a city in Saudi. Hence, using SMRs in Saudi Arabia to generate electrical power can be treated as the primary and additional energy source. Nowadays, the electrical energy transferred from power plants to the delivery point is highly efficient. However, when transferring the power to far-distanced places, the reduction in efficiency may be huge. Hence, building SMRs for such sites is highly recommended.

$$P_{total\ per\ hour} = \frac{Total\ Energy\ Consumed}{Hours\ in\ One\ Year} \qquad (2)$$

$$P_{consumption\ per\ person} = \frac{Power\ Consumed}{KSA\ Population} \qquad (3)$$

$$N_{familes} = \frac{One\ SMR\ Power}{Power\ Consumption\ per\ Family} \qquad (4)$$

The total average annual energy consumed in 2020 in Saudi Arabia is 289,333 GWh as seen in Fig.4, and the average power consumption per hour, using Eq.2, is 33.03 GW. Eq. 3 provides an estimate for the average power consumption per person in Saudi, 943.71 W, which is W/hr consumption by each person. The average family in Saudi consists of 5.7 people [25], and the average power consumption per family in Saudi is 5.43 KW. Eq. 4 concludes that only one unit of 300 MW_e SMR can generate enough electricity for around 55,248 families (314,913 people).

Furthermore, SMRs can be multi-units, with each unit of the same power. Hence, SMR reactors can be used for far-distanced places in Saudi Arabia. In 2020 the amount of energy produced was around 335,445 GWh. Therefore, one unit of SMR can produce 0.783% of the total energy produced in Saudi Arabia.

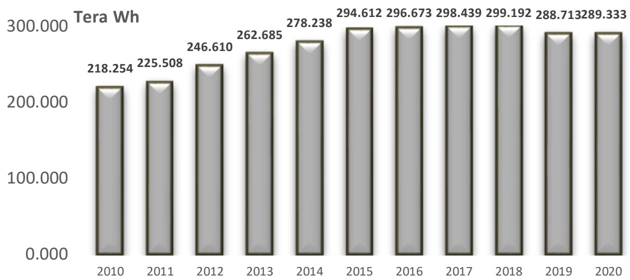

Fig. 4. Annual electricity consumption in Saudi Arabia for the last decade [26]

Saudi Arabia has a population of 34.2 million, and the distribution around the Kingdom in Fig.5. Implementing SMR concept in Saudi Arabia can cover the people and cities in Table.1. For example, two units of 300 MW$_e$ SMR can cover Al-Bahah city or the Northern Borders in the Kingdom. Also, SMR can be an extra unit for an existing power plant. Adding up the power of SMR to the plant can be a smooth solution if the plant does not provide enough power. For example, one of the two large nuclear reactors that will be built in Saudi in 2032 has a 1.7 GW capacity, covering 5.27% of the population. Adding SMR units, in addition to renewable energy sources, will increase the population covered.

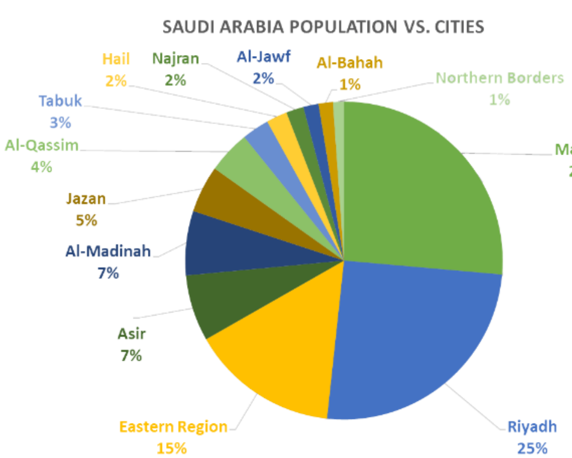

Fig. 5. Saudi Arabia population vs. cities – 2021

In Saudi Arabia, the CO_2 produced directly correlates with fossil fuel energy production. Therefore, if the energy produced comes from an environmentally friendly power source, Saudi can fulfill its vision of zero-carbon emissions by 2060.

Table I Study of % of the population with possible cities covered with No. of SMRs in Saudi Arabia.

Units of SMR (300 MW$_e$)	% of the Population in KSA	Possible Cities Covered
2	1.86	Al-Bahah; Northern **Bord.**
4	3.72	Tabuk; Hail; Najran; Al-Jawf
6	5.58	Jazan; Al-Qassim
8	7.44	Asir; Al-Madinah

SMRs can also be used for steam production for industrial applications. For such purposes, light water reactors are suitable such as PWR. In addition, steam can be used for drying, heating, and sterilizing.

V.C. Hydrogen Production

As a sustainable energy source with potential applications across many industries, hydrogen is gaining popularity. Hydrogen can be utilized as a fuel, a raw material, and in a few other non-energetic applications [27]. In order to reduce CO_2 emissions, the trend nowadays is toward renewable energy sources and hydrogen production. Saudi Arabia has launched a comprehensive new energy mix initiative since the release of Vision 2030, utilizing a range of resources including solar electricity, wind turbines, and nuclear energy. This program seeks to replace major sources of carbon emissions, such as natural gas used in the mining and cement industries, in order to attain net zero carbon emissions by 2060 [28].

A solution for these industries to substantially decrease emissions while maintaining cost-effective operations is hydrogen, which is categorized based on electrical sources and technologies used. Nuclear power is utilized to produce hydrogen implementing a variety of technologies, including steam reforming, thermochemical water splitting, and high-temperature electrolysis, each of which has advantages and disadvantages [29].

Small Modular Reactors, among other nuclear technologies, can be used for hydrogen production. Some SMRs can supply the high-temperature heat required for different hydrogen production processes, including high-temperature electrolysis and thermochemical water splitting. High-Temperature Gas Cooled Reactors (HTGRs), in addition to producing electricity and steam, can deliver high-temperature process heat for the production of hydrogen with coolant outlet temperatures of up to 950°C [29]. The high-temperature engineering test reactor, or HTTR, is one illustration. It is used as a research instrument to produce hydrogen using nuclear process heat. Regarding energy storage, transportation, and power generation, there are anticipated to be substantial advancements in hydrogen production in the near future.

Upon completion of Saudi Arabia's energy mix program and grid connections with GCC countries, Iraq, and Egypt, SMRs can provide further value by producing hydrogen during non-peak hours. This is feasible since nuclear reactors consistently produce energy, and extra power from PV (Photovoltaic) or wind turbines can be used during longer summer days or higher wind speeds at turbine locations. These developments will expand markets and enable new industries.

VI. Future of SMRs with Renewables in Saudi Arabia

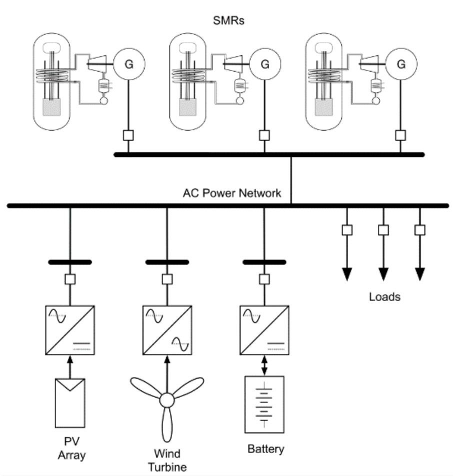

Fig. 6. Example of SMR - renewable microgrid configuration [31]

By the year 2030, renewables and natural gas will make up 50% of the energy mix, based on Saudi Arabia's vision [3]. For example, more than ten projects, such as Saad, Laila, and Al-Rass, are for solar energy. Moreover, projects for wind energy, such as the Dumat Al-Jandal project, to reach net zero emissions by 2060. Although renewable energy is a promising clean energy option for the future, it has drawbacks that compromise its sustainability. The dependency on variable sources, such as wind and sun, limits the reliability of renewables due to the fluctuation in power. Also, the low-capacity factor of some of the renewables, as stated in Fig.1, shows the challenges of renewables to accomplishing the 2030 vision [30].

Furthermore, compensating for such shortcomings is resolved by using mainly diesel generators. Hence, for a cleaner solution, SMRs can be studied to be used effectively with renewable energies for the plans in Saudi Arabia. Using SMRs can balance the fluctuation in power and reduce the energy storage system size in renewable plants in Saudi, example is seen in Fig.6.

VII. Conclusion

To conclude, SMRs, with electrical power reaching 300 MW_e, in Saudi Arabia can be helpful and facilitate reaching net zero carbon emissions by 2060, as the 2030 vision states. Saudi Arabia will develop even more by using such technology for desalination and power production. Using SMR instead of a diesel generator in desalination will help reduce CO_2 emissions from 266.5 g CO_2/kWh to 16 g CO_2/kWh. Also, the cost of producing 1 KWh in NPP is 0.46 $, while it ranges between 0.8 $ – 5.0 $ using a diesel generator. Furthermore, in electricity production, one unit of SMR can generate enough electricity for 0.93% of Saudi's population. Also, one unit of SMR can produce 0.78% of the total energy produced in Saudi. Moreover, SMRs can be the primary power source since two units could cover Al-Bahah city or be an addition to an existing power source. Even more, beside adding value by producing hydrogen during non-peak hours, SMRs can integrate with renewable energy sources due to the possible drawbacks compromising renewable sustainability.

Saudi Arabia is ready to host such technological concepts since the uranium extracting facility has already been constructed, also the agreement between Saudi Arabia and South Korea was signed for launching the SMART reactor in Saudi. In the end, SMRs will be one of the reasons for the development of Saudi Arabia toward a future free of CO_2.

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KACARE	*King Abdullah City for Atomic & Renewable Energy*
KACST	*King Abdulaziz City for Science and Technology*
KAERI	*Korea Atomic Energy Research Institute*
LPRR	*Low Power Research Reactor*
NRRC	*Nuclear and Radiological Regulatory Commission*
NTI	*Nuclear Technology Institute*
SMART	*System Integrated Modular Advanced Reactor*
SNAEP	*Saudi National Atomic Energy Project*
SNEHC	*Saudi Nuclear Energy Holding Company*
SWCC	*Saline Water Conversion Corporation*

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