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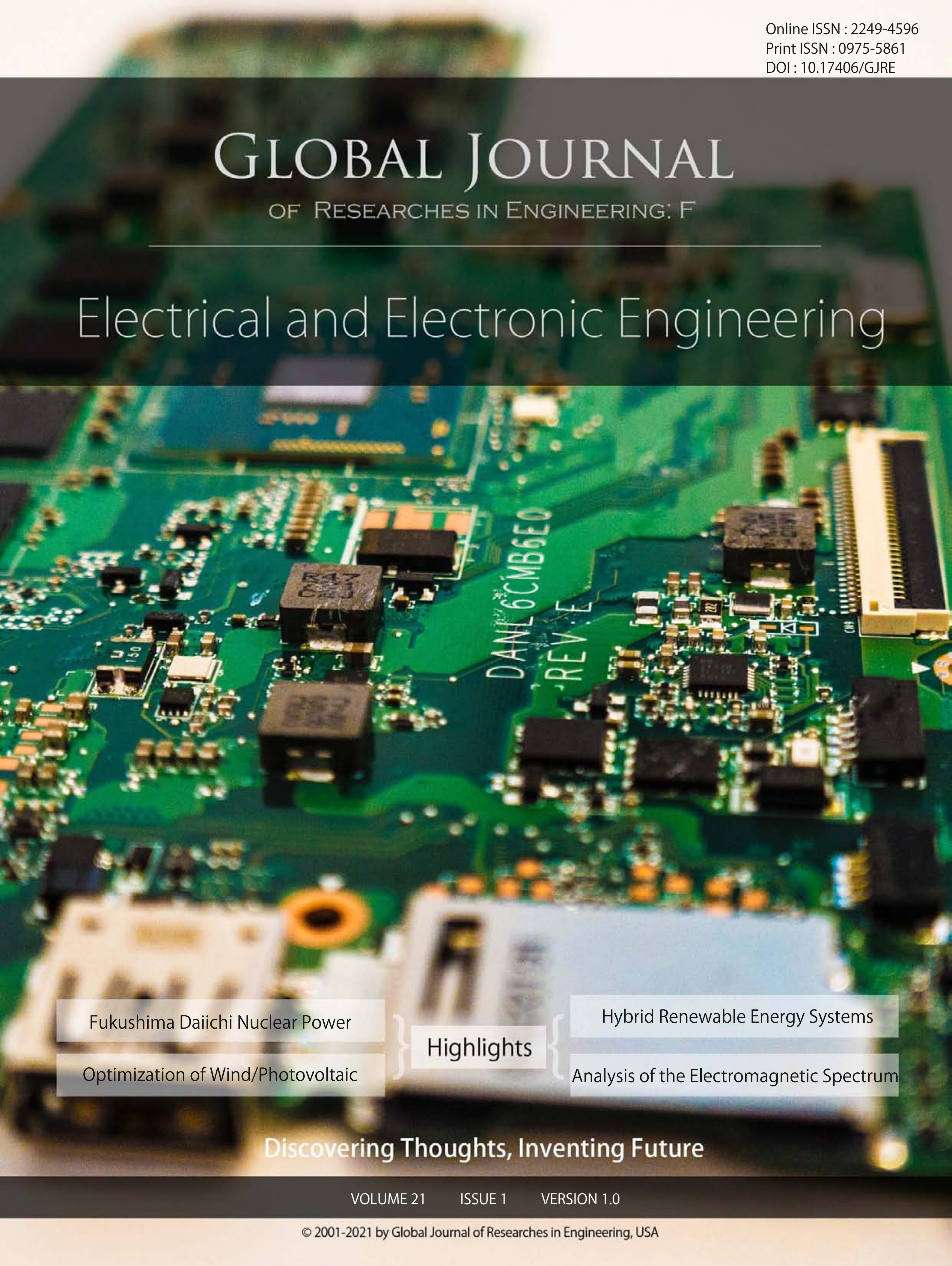

Fukushima Daiichi Nuclear Power

Optimization of Wind/Photovoltaic

Highlights

Hybrid Renewable Energy Systems

Analysis of the Electromagnetic Spectrum

Discovering Thoughts, Inventing Future

VOLUME 21 ISSUE 1 VERSION 1.0

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Validation of Unit 1 of the Fukushima Daiichi Nuclear Power Plant During its Accident

By Shigenao Maruyama

Abstract- Ten years have passed since the Great East Japan Earthquake and the subsequent accident at the Fukushima Daiichi nuclear power plant (NPP) that occurred on March 11, 2011. The earthquake and tsunami caused significant loss of lives and widespread disaster in Japan.

Several reports have been published on the nuclear accident; however, the original data released at the beginning of the accident were written in Japanese, and some of these documents are no longer accessible. Some of the scenarios pertaining to the accident have become standardized theories, and these scenarios may be passed down to future generations with different descriptions, which may not fully describe the actual occurrences. To prevent future nuclear accidents, the accident at Fukushima Daiichi must be properly understood and analyzed.

Keywords: nuclear power plant, accident, isolation condenser, thermodynamic model, fukushima daiichi, great east japan earthquake.

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Several reports have been published on the nuclear accident; however, the original data released at the beginning of the accident were written in Japanese, and some of these documents are no longer accessible. Some of the scenarios pertaining to the accident have become standardized theories, and these scenarios may be passed down to future generations with different descriptions, which may not fully describe the actual occurrences. To prevent future nuclear accidents, the accident at Fukushima Daiichi must be properly understood and analyzed.

Our research group had been analyzing the accident since immediately after its occurrence[2]. To investigate the process of the NPP accidents, Unit 1 of the Fukushima Daiichi NPP was analyzed using data available to the public. A phase-equilibrium thermodynamic model was used in the analysis. We proposed an accident scenario in which the isolation condenser (IC) of Unit 1 may have been working to a certain extent. Moreover, the behavior of the reactor water level meter at the time of the accident was analyzed, and we attempted to reproduce the measurement data of the reactor water level meter and the pressure data measured during the accident. Further more, based on the temperature data of various measuring points and the estimated accident scenario of Unit 1, we also presented a bold estimation of the locations and times of damages in the reactor pressure vessel (RPV) and primary containment vessel (PCV).

In the present study, the original data reported in the first stage of the accident are examined to clarify the behavior of the ICs, which are generally believed to have been nonfunctional after the tsunami and station blackout. The original data and observation reports verified that the so called "fail-safe" system to close the valves in the ICs did not work properly owing to the shutdown of AC power.

This report assumes that the leakage of the RPV occurred at 20:26 on March 11, 2011 owing to overheat of the nuclear fuel clusters. It is estimated that the leakage of the PCV occurred at 03:30 on March 12. A large break in the RPV occurred at 06:20 and again at 16:00. It is estimated that a large portion of the fuel still remains in the RPV; however, the Tokyo Electric Power Company (TEPCO) estimated that most of the fuel had melted out through the RPV. The present analysis model and accident scenario explain the data measured at the accident and several evidences and witness reports that were collected at the early stage of the accident.

The author attempted to boldly predict the positions and times of vessel ruptures according to the present accident scenario. By examining the temperature data of each part of the reactor obtained after March 23, it is presumed that leakages from the RPV at 10:26, on March 11, and 6:20, on March 12, occurred at the safety valves, because the significantly high temperature of the steam that discharged through the valveshad destroyed the valve seats.

Keywords: nuclear power plant, accident, isolation condenser, thermodynamic model, fukushima daiichi, great east japan earthquake.

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I. Introduction

Ten years have passed since the Great East Japan Earthquake and the subsequent accident at the Fukushima Daiichi nuclear power plant (NPP). Approximately one hour before the occurrence of the earthquake at 14:46 on March 11, 2011, the author had landed at Sendai Airport, Japan, on his way back home from a business trip in the People's Republic of China. Three hours after his arrival, the airport was seriously damaged by the tsunami. Hereinafter, the time described is based on the Japan Standard Time. When the author returned to his home in Sendai city, he encountered the earthquake. His home was damaged by the earthquake.

The earthquake and tsunami caused significant loss of lives and widespread disaster in Japan. More than 15,000 people were killed, and approximately 2,500 people are still reported to be missing [1].

At the Fukushima Daiichi NPP, the earthquake caused damages to the external electric supply required to operate the plant. The subsequent tsunami attacked the NPP, resulting in the loss of the cooling function at the three operating reactor units. Then, accumulation of hydrogen gas occurred in the reactor buildings (R/Bs), resulting in explosions at Units 1 and 3. After the reactor cores of Units 1-3 were damaged, a large amount of radioactive materials were released into the atmospheric environment. The water used for the cooling of the damaged reactor cores was contaminated by radioactive substances, which was then spilled and released into the sea.

The author started exchanging information regarding the NPP on March 15. At that time, the possibility of nuclear fuel core blockage due to seawater injection was being discussed with his acquaintances who were nuclear power professionals. The author estimated the current state of the NPP with the help and guidance of nuclear engineering experts and colleagues in academic communities, and disseminated information for early convergence of the accident.

Sendai, where we lived, is located 95 km north of the Fukushima Daiichi NPP. The thermo-fluid analysis of the NPP was conducted using the electric power and the internet restored relatively quickly after the earthquake. We left half of the gasoline in the tanks of our automobiles for the preparations to evacuate from Sendai if something happened to the NPP.

At the first stage, information was distributed to experts in the field of thermal engineering and to the personnel of the Tokyo Electric Power Company (TEPCO), who were introduced by our colleagues. To disseminate information to the public as soon as possible, the Heat Transfer Control Laboratory of the Institute of Fluid Science, Tohoku University, began distributing heat-and-flow-analysis reports on its website from March 28 [2]. Our laboratory posted 26 reports in the two months from March 28 to May 30, 2011. The total number of reports increased to 48 by March 3, 2015.

We started to estimate the decay heat of each unit from open data source, and the data were published on the website [HTC Rep. 1.1, 2011/3/28]. Hereinafter, this report[2] is described as [HTC Rep.#, issued date]. This estimation was corrected, including the operating history of nuclear fuel units [HTC Rep. 1.4, 2011/4/13]. At the time of release of the report, our estimation of the decay heat was different from that provided by TEPCO; however, the estimation presented by TEPCO at the later date became almost identical to our data.

We estimated the steam generation rate of each unit and calculated the ruptured area of the primary containment vessels (PCVs) using the plant parameters such as pressure and temperature. The flow rate calculation method utilizing an orifice was applied to the analysis. We reported that the estimated ruptured area on the PCV of Unit 1 was equivalent to a diameter of 9 cm and that on the suppression chamber (S/C) of Unit 2 was 20 cm, based on the plant parameters obtained on March 26, 2011 [HTC Rep. 14.2, 2011/5/11].The ruptured area on the PCV of Unit 3 was estimated to be equivalent to a diameter of 23 cm based on the plant parameters obtained on May 3. The Japanese govenament and TEPCO had not announced that the PCVs of Units 1-3 were ruptured when we released the report on May 11. Then TEPCO announced on May 25 that the PCVs of Units 1 and 2 may have ruptured, and the equivalent diameters of the ruptures on Units 1 and 2 were 7 and 10 cm, respectively.

TEPCO published an estimation of fuel core conditions of Units 1-3 on May 16, 2011 [3], using a large computer simulation code "Modular Accident Analysis Program (MAAP)." It was reported that the operator restarted the isolation condenser (IC) system A (IC-A) of Unit 1 at 18:18,on March 11, and the ejection of steam from the R/B was confirmed. It was stopped at 18:25, and restarted again at 21:30.

However, TEPCO assumed that the IC of Unit 1 did not work after the station blackout. According to the analysis based on MAAP, the fuel core was damaged 15 h after the tsunami attack, and all the fuel melted out from the reactor pressure vessel (RPV). TEPCO mentioned that "From the analysis results, fuel core damage started relatively early after the arrival of the tsunami, resulting in damage to the RPV. However, considering the state of the plant estimated from the temperature shown below, the analysis seems to be a a severe consequence" [3]. However, TEPCO maintained the assumption that the IC did not work in their subsequent reports [6], [12].

After this announcement [3], all mass media reported sensationally that the Fukushima Daiichi NPP had melted down. TEPCO also assumed that the IC of Unit 1 was not functional after the station blackout caused by the tsunami. This assumption was followed by a government report [4] stating that "Unit 1 lost its all power supplies shortly after the arrival of the tsunami. The isolation condensers (IC) seemed to have lost its functionality as its isolation valves were fully or almost fully closed by the fail-safe circuits." The International Atomic Energy Agency (IAEA) followed this assumption [5].

However, some key evidences showed that the IC was working. For example, there are original records that the operator restarted IC-A, and steam ejection was observed from the R/B. There are records that the water was injected into the reservoir tank of the IC. As presented in Section 3, the reactor water level indicator shows the correct value when the water level is above the top of active fuel (TAF). The records of the water level meter show that the measured water levels were above the TAF at almost constant values from 21:30 on March 11 to 06:30 on March 12. TEPCO explained in the report on June 20, 2012, that "Therefore, water levels measured after core damage are assumed to be unreliable, while water levels taken via analysis are assumed to be closer to those in reality" [6].

We assumed that the IC was, to a certain extent, functional after the station blackout, and estimated that the breakdown of the RPV occurred considerably later than the estimation presented by TEPCO [HTC Rep.17.2, 2011/5/30]. In the analysis, a simple energy balance [HTC Rep. 1.4, 2011/4/13] was considered. The details are described in a published paper [7]. We constructed a more detailed thermodynamic model to describe the equilibrium state of the RPV and PCV of each unit. We determined that the measured data and original record were well described by the simulation using a thermodynamic model.

The simulation program used by TEPCO, the MAAP, is a large system; moreover, it requires a relatively long central processing unit (CPU) time to calculate one accident scenario. Conversely, our program is small and was operated in Microsoft Excel. Our simulation can be used to calculate one set of the accident scenarios within a few seconds, and related diagrams are illustrated promptly. This significantly short turnaround time helped us to simulate large number of accident scenarios to fit the measured plant parameters at the time of the accident. In the analysis of Unit 1, we estimated that the IC was functional until around 03:00on March 12, 2011 [HTC Rep.26.1 2013/02/10], [9].

The Atomic Energy Society of Japan estimated that the AC-driven valve of the IC was fully open when the tsunami struck, and questioned the scenario in which the IC did not work at all after the arrival of the tsunami [10].The Nuclear Regulation Authority of Japan (NRA) examined the status of the IC valves at the time of the tsunami attack, and reported that “However, the operating status (open/close) of isolation valves (1A and 4A) of the IC (system "A") in the PCV is not clear. It is therefore necessary to continue analyses of this issue.” [11]. TEPCO followed up the report [6] on unsolved issues in the accident progression and published additional reports [12] – [16]. TEPCO carried out a simulation where the IC was working in the third progress report [14], which was published on May 20, 2015.The report stated that “But in the overall progression of the accident it would be quite likely the there is a minor difference from what actually occurred in Unit1.” There was no explanation in the report on why the measured water level showed constant values in the early stages of the accident.

Our accident scenario assumed that the IC was functional until approximately 03:00 on March 12, 2011[HTC Rep.26.1 2013/02/10], [9]. This scenario can explain the measurements of the reactor water level in the early stages of the accident. The reactor water level meter shows different value from reality when the water level is below the TAF. We could reproduce the measured water level data by considering the structure of the reactor water level meter [HTC Rep.32.2, 2014/03/05]. We could also reproduce the data when the water level was lower than the TAF. TEPCO attempted to reproduce the measured data of reactor water levels based on the scenario proposed by TEPCO in the fourth progress report[15], which was presented on December 17, 2015, which is 1.5 years later than our report.

According to the above-mentioned analysis using the thermodynamic model and plant parameters on October 10, 2012, we estimated the location of rupture on the PCV [HTC Rep.25.1, 2012/12/26], [9], and we presumed that the location of the rupture was at the bellows that connects the bottom of the dry well (D/W) and the S/C of the PCV. TEPCO examined the interior of the R/B using a robot and determined on May 27, 2014 that water was leaking from the cover of an expansion joint on a vacuum break line; moreover, they estimated that the rupture occurred at the vacuum breaker tube bellows near the bottom of the D/W. This location is considerably close to the location estimated by us on December 26, 2012, which was1.5 years before the findings of TEPCO [13].

In our analysis [HTC Rep.26.1 2013/02/10], [9], we assumed a very small leakage from a rupture equivalent to a diameter of 0.86 cm on the RPV of Unit 1. The NRA examined the plant data immediately after the tsunami attack, and reported that “The NRA could not find any plant data indicating the coolant leak from the reactor pressure boundary between the earthquake occurrence and the tsunami arrival” [11].

Based on this finding, we proposed a new accident scenario in which a small leakage occurred at a safety valve (SV) of the RPV at 20:26 on March 11, 2011, and a large leakage occurred at 06:20 on March 12 at another SV [HTC Rep.35.1, 2015/03/03]. The rest of the second scenario was similar to the previous one [9]. We also boldly anticipated the locations of the rupture on the RPV of Unit 1 according to the temperature data after the accident [HTC Rep.32.2, 2014/03/05].

According to our accident scenario and the simulation of Unit 1 [HTC Rep.35.1, 2015/03/03], it was estimated that fuel leakage occurred approximately at 16:00 on March 12, 2011, which was considerably later than the estimation presented by TEPCO [16]. Moreover, we estimated that a significant portion of the fuel remains in the RPV. This estimation was verified by the temperature data of the unit obtained after March 21 [HTC Rep.32.2, 2014/03/05]. TEPCO estimated that all the fuel in the RPV had leaked out and mentioned that “most of the molten fuel generated at the accident fell down to the lower plenum below the reactor pressure vessel” [16].

We performed a similar simulation of Unit 2 using a similar thermodynamic model, and these results are published in [8]. Our accident scenario and simulation results pertaining to Unit 2 show results similar to those of TEPCO [16], which were determined using the large simulation code MAAP. Our result pertaining to Unit 2 shows better agreement with the measured data at the accident than the analysis presented by TEPCO.

We conducted a simulation of Unit 3 using a similar thermodynamic model, and these results are published in [17] and [18]. Our simulation results are different from those of TEPCO. We estimated that the PCV of Unit 3 ruptured at 09:05 on March 13, 2011. We estimated the ruptured area using the plant parameters and decay heat at the accident and determined that the equivalent diameter of the ruptured area was 15 cm

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[17]. The temperature in the PCV and RPV of Unit 3 is considered to have increased on March 22, because the water injection into the reactor core became significantly small. We estimated that the ruptured area increased to approximately five times larger size than the initial one. It is estimated that the seal on the upper flange of the PCV was damaged on March 22 caused by the high-temperature condition at that time [17].

TEPCO estimated that the decrease in pressure in Unit 3 on the morning of March 13 was due to the fact that the safety relief valve (SRV) was opened, and the vent was operated successfully [6]. On May 2014, water leaks were identified around the expansion joint where the PCV penetrated the main steam pipe D [13]. This indicates that leakage occurred at the bellows of the expansion joint. This finding supports our estimation at that time pertaining to the rupture of the PCV [17]. The NRA confirmed that there was strong contamination on the underside of the shield plug installed on top of the PCV of Unit 3 [19]. This may support the fact that the seal on the upper flange of the PCV was damaged [17].

The author published a book describing the progress of the accident at the Fukushima Daiichi NPP [20]. The events pertaining to the Fukushima Daiichi NPP, Units 1-4, that are dealt with in this book are based on the reports [2] published up to August 2012. The behaviors of the Japanese Prime Minister, Cabinet members, TEPCO executives, and the Director of the Fukushima Daiichi NPP were described based on the facts reported in mass media during and after the accident. Their behavior was described to synchronize with the accident scenarios of Units 1-4 that were presented in our report [2]. Comparing the content of this book with the testimony of the Director of the Government Accident Independent Investigation Commission [21] published after the publication of the book [20], both reports agreed well [HTC Rep.33.1, 2014/6/22]. The words and actions of the members of the office of the Prime Minister and those of the TEPCO executives also agreed well with the reports in this book [20].

The book was written based on our accident scenario before August 2012. However, there are several discrepancies in the analysis of the author [7]. For example, in the first scenario by [7], the author cannot describe why the radiation dose in the R/B increased on March 11at 21:51, while the water level at that time was above the TAF. The pressure in the RPV was high when water was injected at 06:20 on March 11 and water could not be injected under the previous scenario.

TEPCO reported that the injected water may not have reached the RPV because the bypass line was constructed in the reactor system. Consequently, based on the findings of the bypass line, the author constructed a new scenario and analyzed the pressure and water level of Unit 1 [HTC Rep.26.2, 2013/03/03] using a thermodynamic model to analyze the accident behavior of Unit 1. The previous accident scenario [9] assumed a small leak in the RPV immediately after the earthquake. The PCV was estimated to rupture at 03:00 on March 12 and the RPV rupture occurred at approximately 06:20 and 16:00 on March 12. The IC was estimated to be functional until approximately 03:00 on March 12. The pressure estimations of the PCV and RPV were in good agreement with the measured data [HTC Rep.26.2, 2013/03/03].

The Atomic Energy Society of Japan reported that the initial leak of the RPV may not have occurred, according to the measured data of the PCV obtained before the arrival of the tsunami [10]. This fact indicates that the scenario [9] that assumes the initial leak of the RPV may not be suitable.

Ten years have passed since the accident at the Fukushima Daiichi NPP. According to TEPCO, the decommissioning process is expected to be completed in another 20-30 years. Several reports have been published on the nuclear accidents, such as [4], [5], [10], [23]. However, the original accident data and records are gradually becoming lost. Some of the original data released at the beginning of the accident are no longer accessible. Certain scenarios of the accident, which is different from what actually happened, have become standardized theories and may be passed down to future generations. To prevent future nuclear accidents, the accident at Fukushima Daiichi must be properly understood and analyzed. Our analysis of the accident [2] may not always be accurate. Even our latest accident analysis may not agree with the actual measured data, or with our own records at the time.

In this study, we verified that if the IC of Unit 1 of the Fukushima Daiichi NPP may have been working normally to a certain extent, and performed an analysis based on that accident scenario. Moreover, the behavior of the reactor water level meter at the time of the accident was analyzed, and an attempt was made to reproduce the measurement data of the reactor water level meter during the accident. Furthermore, based on the temperature data of various measuring points and the estimated accident scenario of Unit 1, we also make a bold estimation of the damaged positions of the RPV and PCV of Unit 1 as well as the times of the damage.

II. Outline of the Accident at Thefukushima Daiichi Nuclear Power Plant

The Great East Japan Earthquake occurred on March 11, 2011 at 14:46. The epicenter was 130 km east-southeast of the Oga Peninsula in the Pacific Ocean. This earthquake was caused by an energy release at the border of the Pacific tectonic plate and the North American tectonic plate. The earthquake had a magnitude of 9.0, and the tremors lasted for more than two minutes.

Tsunamis following the earthquake struck a wide area of the northeastern coast of Japan. Several waves reached heights of more than 10m, the largest since the Jogan Earthquake, which occurred in the year of 869, approximately 1150 years ago. The earthquake and tsunami caused significant loss of lives and widespread disaster in Japan. More than 15,000 people were killed, and approximately 2,500 are still reported to be missing [1].

At the Fukushima Daiichi NPP, operated by TEPCO, the earthquake caused damage to all external electric supplies required to operate the plant. The subsequent arrival of the tsunami at the NPP destroyed the emergency power supplies and the operational safety infrastructure on the site. This resulted in the loss of the cooling function at the three operating reactor units.

Consequently, the reactor cores in Units 1, 2, and 3 were overheated owing to the decay heat of the nuclear fuel, and the three PCVs ruptured. Hydrogen gas was released from the RPVs and leaked through the PCVs. The hydrogen gas accumulated in the R/Bs, which resulted in explosions in Units 1 and 3.

Radio nuclides were released from the NPP to the atmosphere and were deposited on land. The radioactive water that is used to cool the plant was released directly into the sea. People within a radius of 20 km from the NPP site and in other designated areas were evacuated. Those within a radius of 20-30 km were advised to voluntarily evacuate. Ten years after the accident, many people still live outside the evacuated areas.

Details of the accident before 2015 have been presented in many reports, such as [4], [5], [10], [23].The interior of the reactors has not yet been revealed. The amount of cooling water that is contaminated by tritium is still increasing, and the storage tanks will be full at the NPP site. The Japanese government is planning to release the contaminated water into the ocean by diluting it with seawater.

An outline of the accidents occurred in Units 1-6is subsequently presented.

a) *Before the Tsunami Attack*

The Fukushima Daiichi NPP in Fukushima prefecture consisted of six units of boiling water reactors (BWRs), as listed in Table 1. The BWR units were constructed between 1971 and 1979, and the oldest unit had been in operation for 40 years at the time of the accident. During the operation, several facilities have been replaced, except for the primary structures such as the RPVs, PCVs, and buildings.

When the earthquake occurred, Units 1, 2, and 3 were operating at full power, and Units 4, 5, and 6 were shut down for periodic inspection and maintenance. Unit 4 was stopped for repairing the shroud in the PRV. The spent fuel pool of Unit 4 contained more than 1,300 spent fuel and active fuel assemblies from the reactor. Units 5 and 6 were shut down for periodic inspection, and the fuel assemblies were in the PRVs.

Table 1: Specifications of the units of the Fukushima Daiichi nuclear power plant and the status at the time of the accident

Unit Number	1	2	3	4	5	6
Nominal Power (MW)	460	784	784	784	784	1,100
Date of Operation Start	26/3/1971	18/7/1974	27/3/1976	12/10/1978	18/4/1978	10/24/1979
Type of RPV	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Type of PCV	Mark I	Mark I	Mark I	Mark I	Mark I	Mark II
Main Contractor	GE	GE/Toshiba	Toshiba	Hitachi	Toshiba	GE/Toshiba
Status at the time of accident	Rated operation	Rated operation	Rated operation	Under maintenance for repairing shroud	Periodic inspection	Periodic inspection

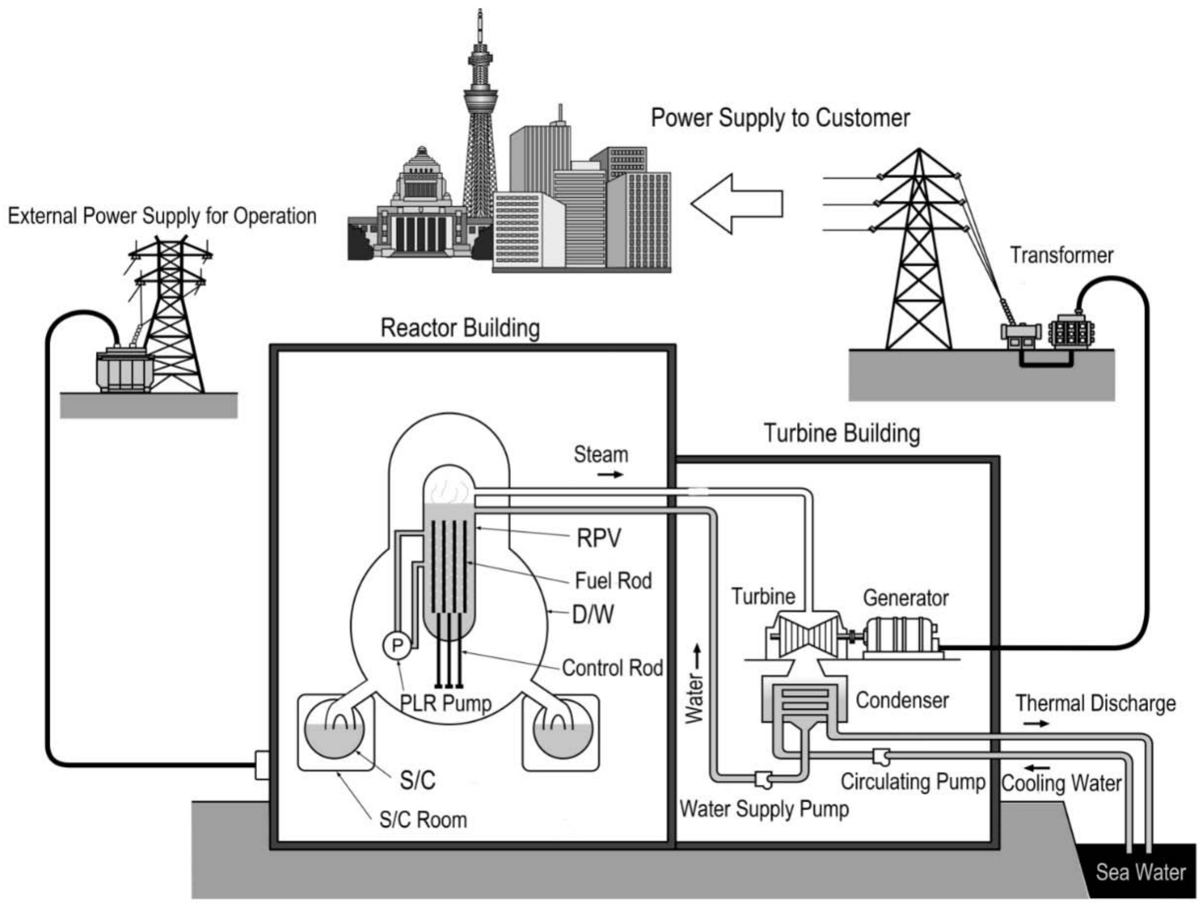

Fig. 1: Overview of the boiling water reactor plant before the tsunami attack [20]

BWRs use a steam cycle loop, as shown schematically in Fig. 1. Coolant water boils in the reactor core at a pressure of approximately 7 MPa, and the generated steam is used to drive turbines to generate electricity. After passing through the turbines, the steam is condensed back to water in condenser tubes that are circulated with cold sea water. The water resulting from condensation is pumped back to the reactor as feed water.

In the case of the Fukushima Daiichi NPP, the produced electricity was delivered to the Tokyo area. NPPs require an external power supply to operate the plants. This electric power was supplied by the Tohoku Electric Power Company because the location of the Fukushima Daiichi NPP is within the jurisdiction of this company, which is different from the Tokyo Electric Power Company (TEPCO). This external electric power is used to cool down the fuel core after the NPP is shutdown.

Units 1-4 were built 10 m above sea level, and Units 5 and 6 were on the ground level, 13 m above sea level. Units 1 and 2 were controlled by a main control room, and Units 3 and 4 were controlled by another main control room. A seismically isolated building was constructed for an emergency accident of the NPP one year before the accident. This building had emergency electric generators and air cleaners to prevent the entry of radio active materials into the building. A local emergency headquarter was set up in the building in the occurrence of an accident.

When the Great East Japan Earthquake of magnitude 9 occurred, the recorded maximum acceleration at the Fukushima Daiichi NPP was 550 gal. The operating reactors of Units 1, 2, and 3 were shut down automatically and the fission reaction in the reactor cores was stopped. However, these reactors had to be cooled because decay heat was generated inside the reactor cores. The earthquake caused damage to the switchboard equipment, and the external AC power supply from Tohoku Electric Company to the plant was shut down. The emergency diesel generators automatically started to restore the AC power in all six units. The ICs in Unit 1 started automatically to cool the reactor. The operators manually activated the reactor core isolation cooling systems (RCICs) in Units 2 and 3.

b) After the Tsunami Attack

The initial tsunami waves arrived at the NPP approximately 40 min after the earthquake. The site was protected from the first wave by a barrier seawall, which was designed to protect the land against a tsunami of 5.5 m height. The second tsunami wave arrived at 15:36. It was estimated to be more than 14.5 m high. This tsunami attacked the NPP and destroyed the emergency diesel generators and DC batteries. A station blackout was declared for Units 1-5 at 15:42. The residual heat removal system (RHR) did not function because of the station blackout.

At the time of the tsunami attack, the situation at each unit was as described subsequently.

Unit 1: The emergency diesel generators were damaged, and the AC power was lost. The DC batteries became nonfunctional owing to the invasion of seawater. IC system B (IC-B) was manually stopped before the tsunami attack, and IC-A was manually operated before the arrival of the tsunami. When the tsunami hit the NPP, the valve of IC-A was closed, and the IC was not activated.

Unit 2: The emergency diesel generators were damaged, and the AC power was lost. The DC batteries became nonfunctional owing to the invasion of seawater. The RCIC was started just after the arrival of the tsunami. Fortunately, the RCIC worked until 13:00 on March 14, without the DC power.

Unit 3: The emergency diesel generators were damaged, and the AC power was lost. The DC batteries survived against the tsunami attack. Using the DC power, the emergency core cooling systems were operated until 02:42 on March 12.

Unit 4: The fuel assemblies from the reactor fuel were stored in the spent fuel pool, and the fuel was generating decay heat. The cooling function of the spent fuel pool was lost owing to the loss of the external power supply and emergency generators.

Units 5 and 6: The batteries were not damaged, and DC power was available. An air-cooled emergency diesel generator in Unit 6 survived the tsunami attack. Using the AC power from this operational generator, the operators managed to cool the decay heat in the reactor cores. Finally, the reactors stabilized.

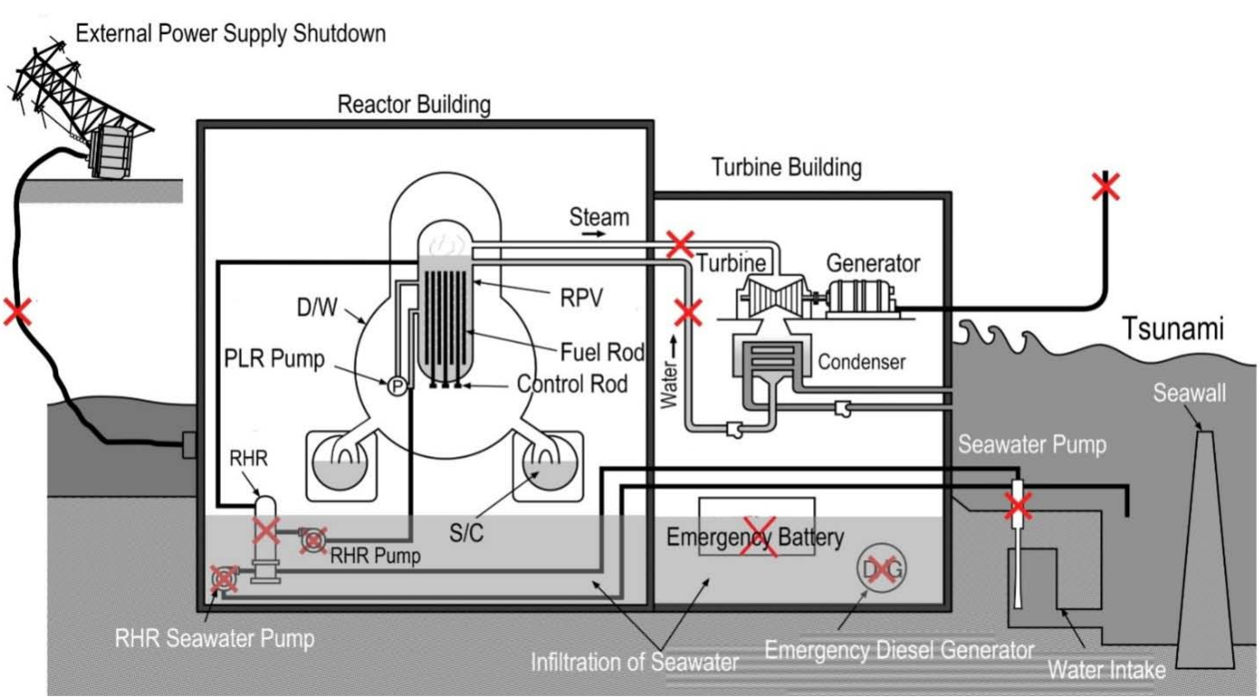

Fig. 2: Situation at the nuclear power plant (NPP) after the arrival of the tsunami at 16:00 on March 11, 2011[20]

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c) Explosion of the Reactor Buildings of Units 1 and 3

Unit 1: The cooling function of Unit 1 was lost on the night of March 11, and the PCV exceeded its maximum design pressure at 23:50 on March 11. The radiation level at the main gate of the NPP increased at 04:00 on March 12, and TEPCO attempted to inject water into Unit 1.An explosion occurred in the R/B of Unit 1 at 15:36. The explosion damaged the R/B; however, the PCV was not damaged. This explosion was caused by the accumulation of hydrogen gas that was generated by the chemical reaction between the high-temperature zirconium and water vapor in the fuel core.

Unit 3: Immediately after the tsunami attack, the DC batteries of Unit 3 were functional, even though the emergency AC generators were nonfunctional. Hence, the RCIC of Unit 3 was working at that time. The RCIC became in operative at 11:36 on March 12; then, the high-pressure coolant injection system (HPCI) started automatically owing to the low water level in the RPV. The HPCI was stopped at 02:42 on March 13. Fresh water was injected into the RPV at 09:25, and the seawater was injected at 13:25 by venting the internal gas into the environment. An explosion occurred at 11:01 on March 14 in the R/B. This explosion was caused by the accumulated hydrogen gas that was generated by a chemical reaction between the high-temperature zirconium and water vapor in the fuel core of Unit 3.

d) Rupture of the PCV of Unit 2 and the Explosion of the Reactor Building of Unit 4

Unit 2: According to the report of TEPCO [6], the RCIC repeated an automatic stop function owing to water level in the RPV and manual restarting was performed before the tsunami attack. The RCIC was stopped automatically at 15:28, and the tsunami attacked Unit 2 at approximately15:35. The operator restarted the RCIC manually at 15:39. Owing to the tsunami attack, the emergency diesel AC generators and DC batteries in Unit 2 became nonfunctional at approximately15:41. The RCIC was working, and the appropriate valves were open when the blackout occurred.

Fortunately, the RCIC of Unit 2 was working without electricity. It was presumed that the turbine and pump powers were balanced and the RCIC continued working for almost 70 h without any control after the blackout. Finally, the RCIC became nonfunctional at 10:30 on March 14.

The seawater injection into the RPV started at 19:54 on March 14, and the pressure in the RPV was reduced by manually opening the SRV. Owing to the release of the internal gases of the RPV into the PCV, the pressure in the PCV increased; however, the pressure in the PCV could not be reduced because the depressurization by venting was unsuccessful.

Owing to the pressure increase in the PCV, the PCV ruptured at approximately 06:00-08:00 on March 15, and a large amount of radioactive materials was released into the environment. White smoke or steam was observed near the fifth floor in the R/B of Unit 2. The radiation dose measured at the main gate at approximately 09:00 was 12mSv/h, which was the highest since the beginning of the accident.

Unit 4: Vibrations due to the explosion were reported at 06:14 on March 15 by the operators in the main control room of Units 1/2. These vibrations were caused by the explosion of the R/B of Unit 4 at 06:12 [6]. The evacuating personnel reported that the upper part of the R/B blew out at approximately 06:00 on March 15.

It was presumed that this explosion was caused by the hydrogen gas released from Unit 3. The process of venting the internal gases and steam was repeated in Unit 3 after its explosion at 11:01 on March 14. This venting process was conducted using the standing gas treatment system (STGS) line and the exhaust stack. Units 3 and 4 used the same exhaust stack, and the STGS lines of Units 3 and 4 were connected. TEPCO estimated that a part of the produced hydrogen gas in Unit 3 was accumulated in the R/B of Unit 4, and the hydrogen gas exploded.

The spent fuel pool on the fifth floor of the R/B of Unit 4 contained more than 1,300 fuel assemblies, including the active fuel assemblies from the reactor. These fuel assemblies from the reactor core produced a large amount of decay heat. The cooling function of the spent fuel pool was lost owing to the blackout of Unit 4.

The US government was concerned with the blackout and explosion of Unit 4, and the damage to the spent nuclear fuel pool, which could result in a large discharge of radioactive materials. Consequently, the US government issued an evacuation advisory to Americans staying within a radius of 50 miles from the Fukushima Daiichi NPP on March 16. However, it was confirmed that water existed in the pool; moreover, water was filled stably into the pool using concrete pump vehicles from March 22.

e) Release of Radioactive Materials

After the reactor cores of Units 1-3 were damaged, water was injected into the RPVs. The evaporated steam and radioactive materials were released into the atmospheric environment. Immediately after the explosions of the R/Bs, seawater was injected, followed by the injection of fresh water from March 25. The spilled water that was contaminated by the radioactive materials was released into the sea through the trench, which is an underground tunnel for storing pipelines and cables.

The IAEA [5] reported that the released mean total activity of ^{131}I (half-life time is 8 days) was 100-400 PBq, and that of ^{137}Cs (half-life time is 30 years) was approximately 7-20 PBq. The unit, 1peta-becquerel, equals 10^{15} Bq. The release of radioactive materials owing to the accident was estimated to be

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approximately one-tenth of the radioactive materials released owing to the accident in 1986 at the Chernobyl NPP. The direct release of ^{131}I into the sea was estimated to be 10-20 PBq, and that of ^{137}Cs was approximately 1-6 PBq.

TEPCO constructed a contaminated water cycle, as shown in Fig. 3. The spilled-out contaminated water from the broken RPVs was pumped up and stored in a temporary storage tank. The oil was removed from the contaminated water, and cesium was removed using a facility called Simplified Active Water Retrieve and Recovery System; further, strontium and other radioactive materials were removed using an Advanced Liquid Processing System. The decontamination equipment cannot remove tritium because hydrogen and tritium are the same chemically and physically. The decontaminated water was desalted using a nano-pore film. Purified clean water was injected into the highly contaminated RPVs to cool the decay heat.

This water cycle is basically maintained at present. Water in the outside soil flows into the basement of the reactor and turbine buildings, and it is stored in the tanks constructed on the NPP site. The cooling water contaminated with tritium is increasing, and storage tanks are full on the NPP site. The Japanese government is planning to release the contaminated water into the ocean by diluting it with seawater.

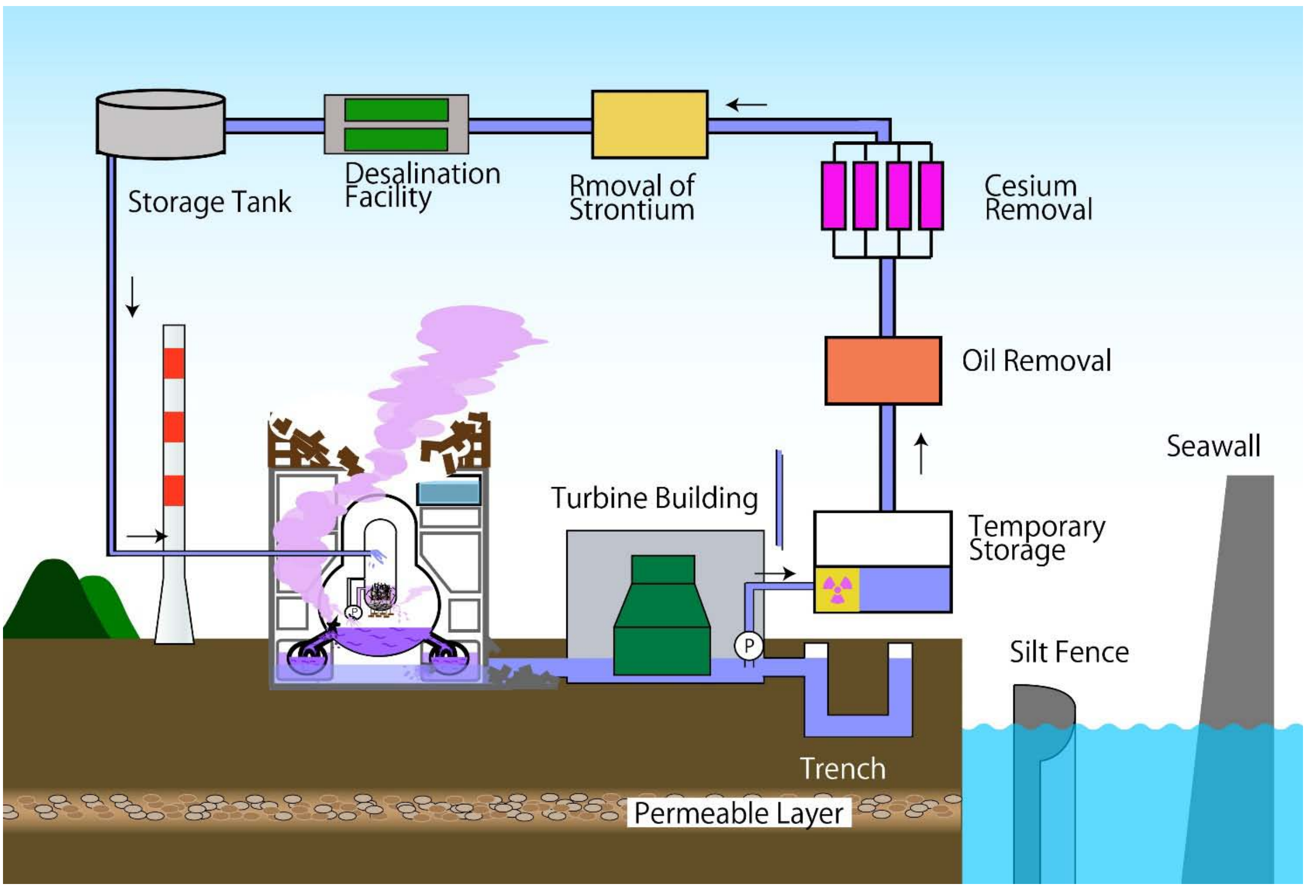

Fig. 3: Status of the contaminated water cycle, as of August 2011 [24]

During the Fukushima Daiichi NPP accident, no one was killed by acute radiation syndrome, which is caused by direct irradiation from the radioactive materials released owing the accident. It was reported that 28 emergency workers were killed because of the acute radiation syndrome within four months of the Chernobyl accident in 1986.

Many people were killed during the evacuation process. For example, 388 elderly patients in a hospital within a 20 km radius were evacuated in normal buses after the explosion of Unit 3. They are transported without proper care, and 21 died during and after the evacuation process. Many other people died after the evacuation owing to mental and physical diseases caused by the evacuation.

III. Behavior of Isolation Condensers (ICs) of Unit 1 During the Accident

a) Structure of ICs and Reactor Water Level Meter

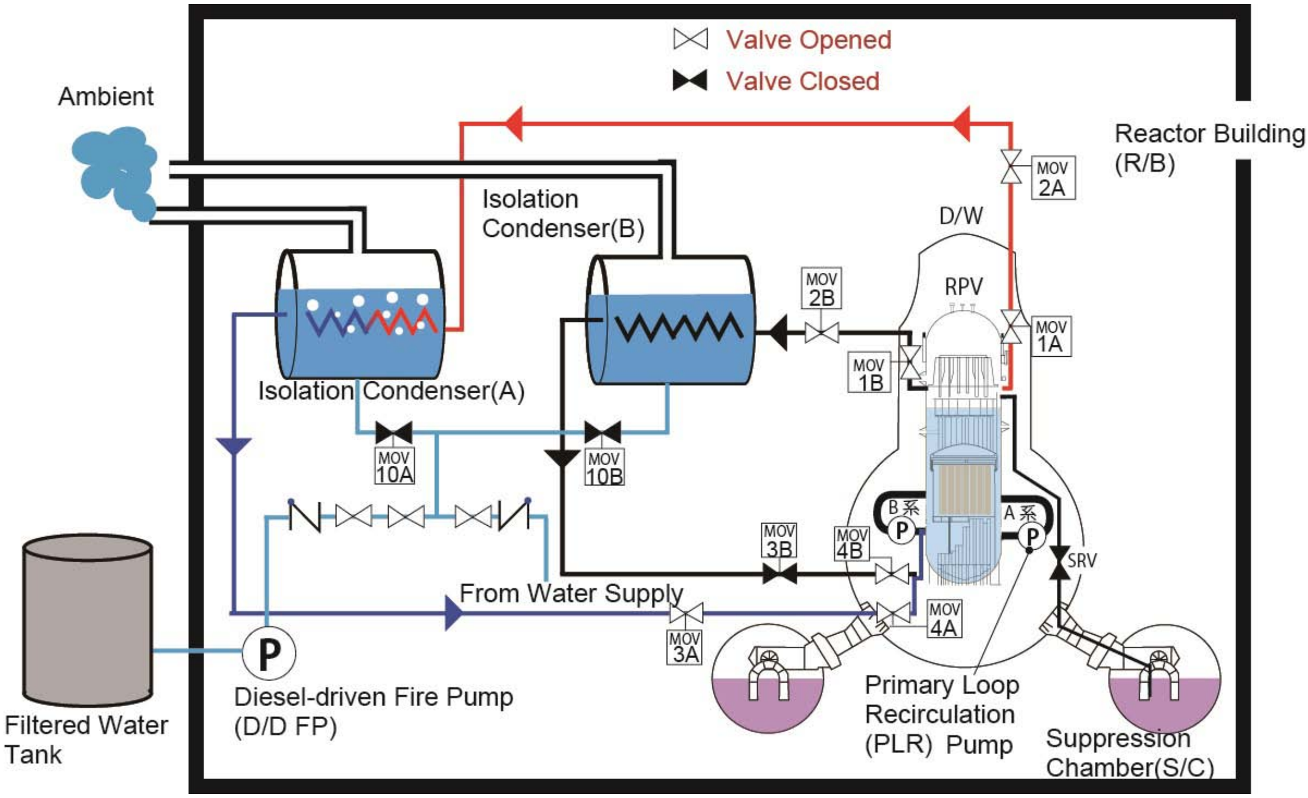

Fig. 4: Structure of isolation condensers (ICs) and main steam safety release valves (SRVs), and their arrangement in Unit 1 [9]

Unit 1 of the Fukushima Daiichi NPP was the oldest unit in the NPP and was equipped with ICs for emergency cooling. When a reactor scrams, and the fission reaction stops, the IC cools the decay heat of the fuel cores. The steam released by the decay heat enters the heat transfer tube installed in the IC, and it is condensed by the water in the IC reservoir tank. The condensed water returns to the reactor. The water in the IC reservoir tank evaporates, and steam is released from the R/B. The cooling process by the IC can function without external electric power.

Figure 4 shows the emergency cooling system using the ICs and their valve positions. Four valves connecting each IC and the RPV are attached to IC-A and IC-B. These valves are motor-operated valves (MOVs), which hold their position “as it is” when the electric power supply stops. MOV-1 and MOV-4 are AC motor-driven valves, and MOV-2 and MOV-3 are DC motor-driven valves. The positions of the valves are shown in Fig. 4. MOV-3A and MOV-3B, of systems A and B, respectively, are closed and the other valves are open when the reactor is in operation. The reservoir tank of the IC is connected to a filtered water tank. The water is supplied by a diesel-driven fire pump (D/D FP) when the IC is operated for a long time.

When the reactor was stopped by a scram due to the earthquake, the ICs started automatically. The operator stopped system B, i.e., the operator closed MOV-3B. Moreover, system A was intermittingly operated to maintain the temperature decrease of the reactor within 55 °C/h (100 °F/h). Just before the tsunami attack at 15:36, MOV-3A was closed at 15:34 by the operator.

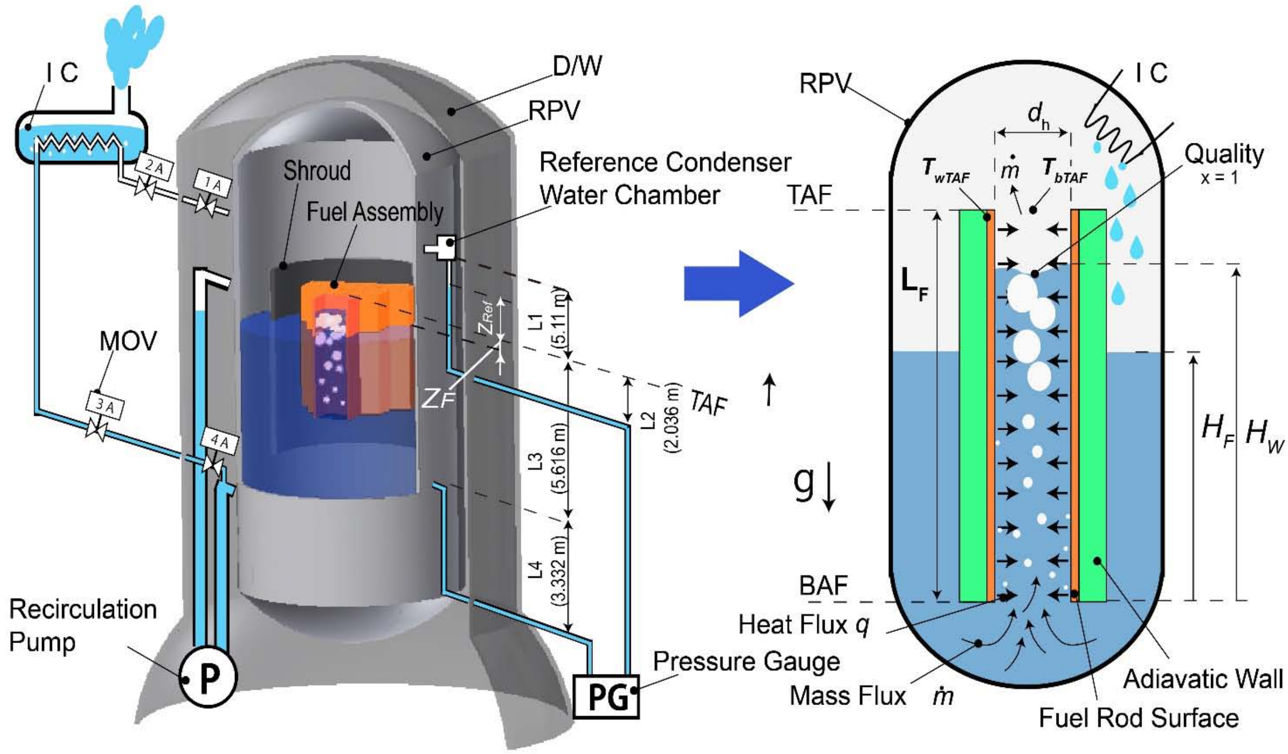

Fig. 5: Structure of reactor water level meter and boiling heat transfer model of fuel assemblies

As discussed in Section 3.3, the reactor water level meters showed constant values in the early stages of the accident. This measurement data is important for verifying the behavior of the IC. Figure 5 shows a schematic of the reactor water level meter. The water level of a BWR is measured by the water head difference between the water level of the reactor fuel region Z_F and the water level Z_{Ref} of the reference condensing water chamber, which is placed outside the RPV. The water level of the reactor fuel region Z_F is expressed as $Z_F = H_F - L_F$ in Fig. 5, when Z_F is lower than the TAF. The reference condensing water chamber is connected to the PRV by a tube. The difference in water heads between Z_F and Z_{Ref} is measured by a pressure gauge placed outside the PCV.

The temperature of the reference condensing water chamber is marginally lower than that of the RPV. Hence, the saturated water vapor in the RPV flows in the chamber and condenses to water in the chamber. The condensed water in the chamber flows back to the RPV. Hence, the water level of the reference Z_{Ref} is equal to L_1. Accordingly, the water level meter shows a constant water head when the water level of the RPV is higher than the TAF. When the water level becomes lower than the TAF, high-temperature unsaturated vapor dries the chamber, and the water level Z_{Ref} in the pipe connected to the reference condensing water chamber falls from the reference heightL_1. Accordingly, the measured apparent water level is displayed higher than the actual one Z_F.

b) Response of TEPCO after the Tsunami Attack

TEPCO released a report [25] that described the actions undertaken by TEPCO based on the plant data measured immediately after the accident. Although this report [25] was published on June 18, 2011, later than the report on May 23 [3], it is believed that the report describes the situation of the NPP immediately after the accident. The facts related to the ICs are summarized as follows:

March 11, 2011

14:46: The Great East Japan Earthquake occurred. An automatic reactor scram occurred.

14:47: Automatic startup of emergency diesel generators occurred.

14:52: The ICs of Unit 1 were confirmed to have started automatically.

Because the reactor water level was at the normal level, it was decided that the HPCI will be activated when the reactor water level drops, and the reactor pressure will be controlled by the IC.

Around 15:03: The reactor pressure in Unit 1 dropped too fast to comply with the reactor cooling-temperature drop rate of 55 °C/h that is specified in the safety regulations, and the return piping isolation valves of the IC (MO-3A and MO-3B) were closed. The other valves were kept open, and in the normal standby state. It was judged that one IC series would be sufficient to control the reactor pressure to approximately 6-7 MPa; consequently, it was decided to control the reactor pressure using system A. Moreover, the reactor pressure control was operated by opening and closing the return piping isolation valve (MO-3A).

15:35: Second wave of the tsunami arrived.

15:37: Loss of all AC power and station blackout occurred

We checked the status of the IC and HPCI for Unit 1 as they were operational equipment with DC power. It was confirmed that the valve open/close indication of IC was not visible.

Around 15:50: The DC power supply for measurement was lost, and the reactor water level became unknown.

We started collecting batteries and cables from companies in the NPP. We brought them to the central control room, checked the drawings, and started connecting them to the instrument panel in the Unit 1/2 central control room.

In the central control room, the indicator lamps of the return piping isolation valve (MO-3A) and supply piping isolation valve (MO-2A) were observed to be ON, probably owing to the temporary restoration of the DC power supply. When we checked the status, we determined that these valves were closed.

18:18: The return piping isolation valve (MO-3A) and supply piping isolation valve (MO-2A) of the IC were opened, and steam generation was confirmed.

18:25: The return pipe isolation valve (MO-3A) was closed.

21:19: The water level in Unit 1 was determined as TAF +200 mm.

21:30: The return piping isolation valve (MO-3A) was opened, and steam generation was confirmed.

21:51: Entry to the R/B was prohibited owing to the increased radiation levels in the building.

22:00: It was confirmed that the water level was TAF +550 mm.

March 12, 2011

02:30: The pressure of D/W reached 840 kPa (Abs).

04:55: It was confirmed that the radiation dose was increased in the NPP from 0.069 μSv/h (04:00) to 0.59 μSv/h (04:23) near the main gate.

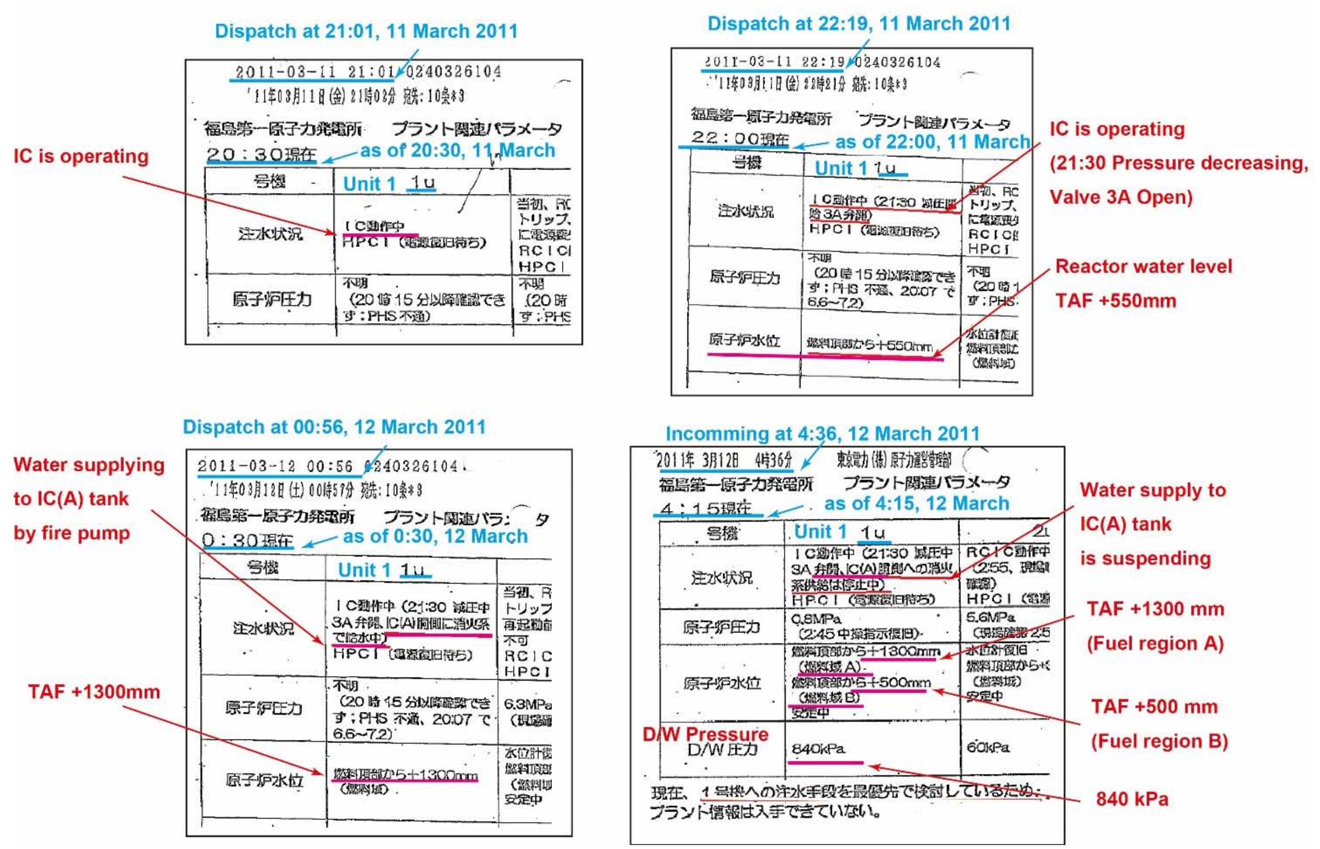

Fig. 6: Behavior of IC system A according to the original records of the plant parameters during the accident. The records were extracted from the original list of plant parameters at the time of the accident (released on June 24, 2011) [26].

c) *Original Records of Accident and Plant Parameters*

The Nuclear and Industrial Safety Agency (NISA) released documents from TEPCO [26]. In this document, original faxes and plant parameters at the time of the accident were included. We examined the large amount of available original data to investigate the accident.

As shown in Fig. 6, there is a description stating "Water supply to IC (A) tank by fire pump" (water is supplying to the resaviour tank of IC(A) by a diesel-driven fire pump(D/D FP) system) in the original plant parameter at 00:30 on March 12. Thus, the D/D FP system shown in Fig.4 may have been supplying cooling water to IC-A at this time. If that is the case, it is highly likely that the water supply stopped before 04:15, because "Water supply to IC(A) tank is suspending" was reported at 04:15.It is possible that the water supply continued until the IC was shut down.

TEPCO considered that the IC was not functional [6], because the so called "fail-safe system" worked after the tsunami attack and all valves connecting the RPV and ICs were shut down. TEPCO measured the amount of water in the IC tank long after the accident [3], and there was sufficient water in the tank. The water volume in the reservoir tanks of ICs measured after the accident was in good agreement with the volume of consumed water that was calculated based on the nonfunctional IC. According to the description in Fig. 6, the amount of cooling water in the tank of IC-A based on the assumption by TEPCO that there was no water supply may have been a coincidence.

In the original list of plant parameters, recorded at 21:30, there is a record that "The IC is in operation." This implies that the IC was in operation at the latest at 20:30. There is another record in the list of plant parameters recorded at 22:30 that the IC was in operation ("pressure decreased at 21:30. 3A valve opened"). These two records contradict each other. From the fact that the IC was in operation as shown in Fig. 6, and from the eyewitness testimony confirming that it is highly likely that the IC was operating as initially reported in the accident.

The Investigation Committee of the Government of Japan [4] concluded that the ICs did not function after the tsunami attack, because as soon as the DC power was off, the AC MOVs were closed by the "fail-safe" sequence. The Committee also accused that the Director of the Fukushima Daiichi NPP was not aware that the IC had stopped, and that this misunderstanding caused the accident to be more serious. It would have been difficult to believe that the IC was shut down when the central control room reported that the IC was operating and there were various eyewitness reports. In addition, the Committee stated that there was no water supply to the IC. This contradicts the records at the time of the accident, as shown in Fig.6.

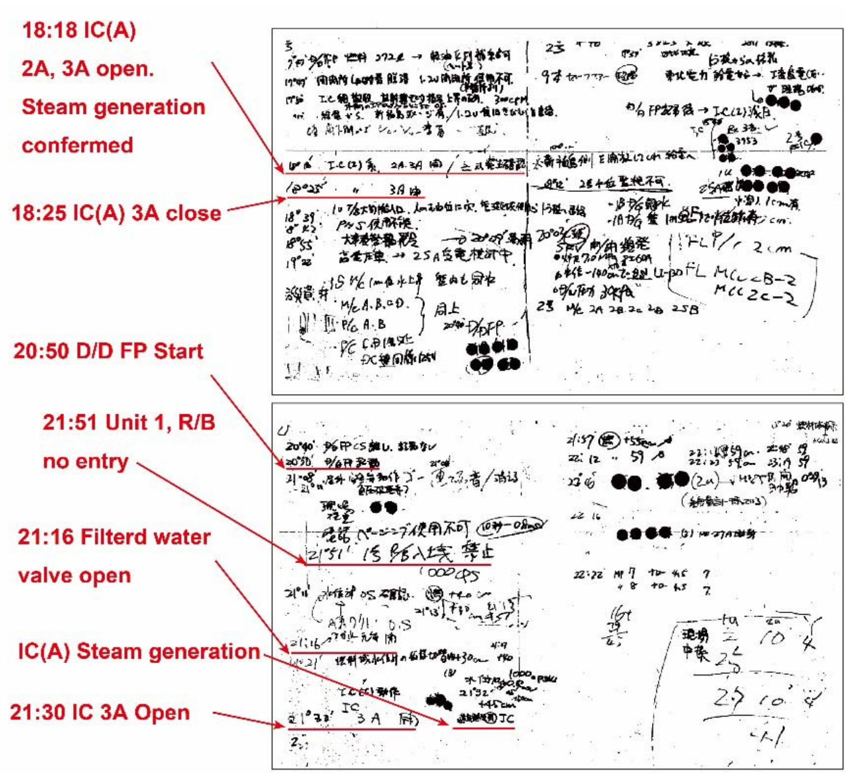

Fig. 7: Records of the white board in the central control room at the time of the accident. The white board records at the time of the accident were taken from the operation logbook reported by Tokyo Electric Power Company (TEPCO) on May 16, 2011 [26].

Figure 7 shows the white board record in the central control room at the time of the accident. According to the record of IC operations, records indicated “20:50 D/D FP start” and "21:16 filtered water valve open” (the main valve for filtered water for cooking the IC was opened at 21:16). Because supplying filtered water by the D/D FP is the standard water supplies to the IC tank, as shown in Fig. 4, it implies that the operators supplied water to the IC tank at this point. This record does not contradict the IC water supply record in Fig. 6. The Investigation Committee of the Government of Japan [4] ignored all these records. These descriptions in the white board imply that the restart of the IC was before 21:30, because it is unlikely that water is supplied before the IC starts. Accordingly we assumed that the IC was restarted at 20:30.

At the initial stages of the accident, TEPCO reported [25] that the IC was operational after the tsunami attack at 15:36 on March 11, 2011. And steam ejection was observed from the IC when the IC was restarted at 18:18, and 21:30. However, TEPCO assumed that the IC did not function after the tsunami attack in their report [6]. They ignored the observed steam ejection at 18:18 and 21:30. They also ignored that water was supplied to the reservoir tank of IC-A at 21:35.

The record on the white board indicates that “18:18 IC(A) 2A, 3A open. Steam generation confirmed” (IC(A) MOV-2A and 3A was opened at 18:18, and steam generation was confirmed),“18:25 IC(A) 3A closed“ (IC(A) MOV-3A was closed at 18:25) and “21:30 IC(A) 3A open”(IC(A) MOV-3A was opened at 21:30), and “IC(A) steam steam generation.” These records are in accordance with the actions of TEPCO immediately after the accident [25], as described in the previous section b.

According to a recent investigation [19], AC power system A became nonfunctional at 15:36:59 on March 11, 2011, and the other line was nonfunctional; a few minutes later. As shown in the previous section b, the DC power was lost at approximately 15:50. The AC-operated valve requires approximately 20 s to closefully, and the DC-operated valve requires approximately 15 s. The fail-safe system is activated when the DC power is lost, and the AC-driven motor valves, MOV-1A, MOV-4A, MOV-1B, and MOV-4B, are automatically closed. It is unlikely that the AC-driven motor valves,MOV-1A and MOV-4A,wereclosed by the fail-safe system.

Long after the accident, TEPCO investigated the valve positions of MOV-1A and MOV-4A to determine if they were fully closed. The AC power in the NPP was recovered between March 20 and March 24, 2011. It is possible that these AC MOVs were closed by the fail-safe signal when the AC power was recovered. As shown in the previous section b, the operators collected batteries and attempted to operate the DC-driven motor valves MOV-3A and MOV-2A. It is highly possible that the valves of the IC were working at the time.

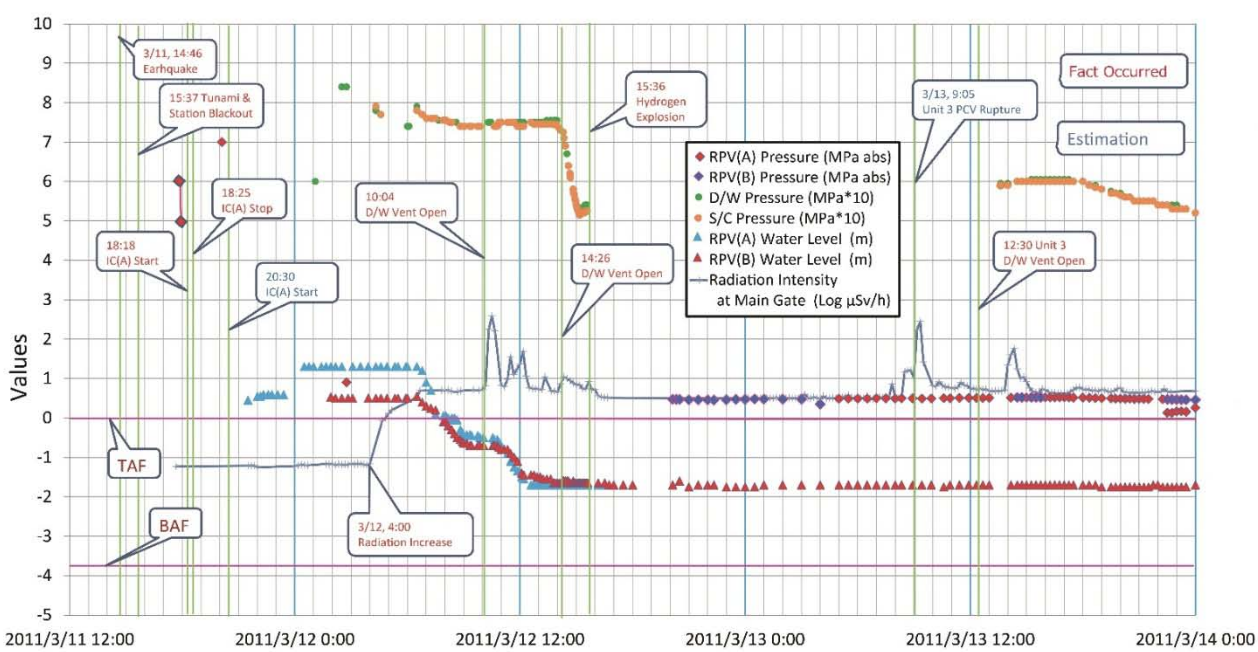

Fig. 8: Measured plant parameters of Unit 1, radiation intensity, and actual occurrences in the accident of the Fukushima Daiichi NPP

TEPCO released the plant parameters of the units of Fukushima Daiichi NPP and measurement data on the radiation intensity at various measurement points in the accident. Figure 8 shows the pressure of the RPV and PCV, or the D/W and S/C, and measured water levels above the TAF. The radiation intensities at the main gate are depicted on a logarithmic scale. The actual occurrences in the accident are indicated in

Fig.8. We consider the time when the IC was restarted to be 20:30 on March 11 rather than 21:30, as reported in the initial report by TEPCO [26], because there is a record that the IC was working at 20:30 in Fig. 6. We think the rupture in the PCV of Unit 3 occurred at 09:05 on March 13, 2011 [17], which differs from the estimation presented by TEPCO [6].

There were two reactor water level meters in the RPV, and their data show different values. The water level was almost constant above the TAF from 21:30 on March 11 to 06:30 on March 12. As shown in the previous section b, the reactor water level meter shows the correct value when the water level is above the TAF. The data may not be accurate, but the discrepancies must be explained reasonably. TEPCO explained in the report on June 20, 2012, that "Therefore, water levels measured after core damage are assumed to be unreliable, while water levels taken via analysis are assumed to be closer to those in reality" [6].

The radiation measurement instruments located at various points in the NPP were working independently without the effect of the station blackout; hence, the data and measured times are correct. The data on radiation intensity have to be rationally explained based on the actual occurrences inside Unit 1 in reality.

We attempted to construct an accident scenario that explains all the data in Fig. 8, and to determine the actual occurrences in Unit 1 during the accident.

d) Behavior of Valves and the Water Reservoir of IC

When the earthquake occurred, the reactors stopped owing to reactor scram, and the ICs started automatically. Then, the operators stopped IC-B, and IC-A was intermittingly operated to maintain the temperature decrease within 55 °C/h or 100 °F/h. MOV-3 of system A was closed when the tsunami arrived.

TEPCO [6] and the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations [4] reported that the "fail-safe system" closed all valves connected to the ICs, and that they did not work after the tsunami. Conversely, TEPCO [13] reported that the AC power shut down occurred at 15:36:59, immediately after the tsunami attack. The DC power is estimated to have been active until at least 15:50[25]. The "fail-safe system" activates when the DC power goes off. These facts imply that the AC MOVs, i.e., MOV-1 and MOV-4, may have been fully open owing to the AC power blackout at the early stage of the accident. This fact was indicated by the author [HTC Rep.26.2, 2013/03/03], [9]. The NRA[19]indicated that MOV-1 and MOV-4 may have been open when the tsunami attacked. The operators attempted to operate IC-A by connecting DC batteries for automobiles. If the DC MOVs were open, it is highly possible that IC-A was operational after the tsunami struck.

TEPCO reported that the amount of water remaining in the reservoir tank of IC-A agreed with the estimated water volume of IC-A if it was not functional after the tsunami. The NISA disclosed the accident data published by TEPCO, where the faxes and original data of plant parameters of reactors were listed [26]. The plant parameter report at 00:30 on March 12 described that the water was injecting into the reservoir tank of the IC-A. As shown in Fig.6, the water was injecting to IC by a D/D FP. According to this evidence, IC-A may have been working at that time. The IC may have stopped before 04:45 on March 12 because there was evidence that the water injection to reservoir tank IC-A is suspending at 4:45, in the original plant parameters report, as shown in Fig. 7. From the previously mentioned data and evidence, it is highly likely that IC-A was functional after the tsunami attack and stopped before 4:45 on March 12.

The water injection to the reservoir tank, and the report of several eyewitnesses (TEPCO operators and workers), who saw steam ejection from the IC, were ignored in the Investigation Committee report on the "Accident at the Fukushima Nuclear Power Stations"[4]. TEPCO also ignored evidence that steam ejection was observed by the workers [25] at 21:30 on March 11. It was also reported in the original plant parameter data that the IC was functional [26]. These facts were ignored in the report of the Investigation Committee [4].

TEPCO claims that the increase in radiation dose in the R/B at 21:51 is an evidence of the early meltdown of the RPV because the IC was not working after the tsunami. However, the present analysis shows that the increase in radiation can be explained by an accident scenario, assuming that the IC was working after the tsunami. Furthermore, the behavior of the water level meters can also be reproduced by an accident scenario where the IC was working [HTC Rep.32.2, 2014/03/05].

IV. Proposed Accident Scenario

In the present accident scenario, we assumed that the IC was, to a certain extent, functional after the station blackout, and the estimated breakdown of the RPV occurred considerably later than the estimation presented by TEPCO. Moreover, we constructed a detailed thermodynamic model to describe the equilibrium state of the RPV and PCV in the NPP. We determined that the measured data and original records are well described by the simulation using the thermodynamic model. Our simulation program is relatively small and operated on Microsoft Excel. It can be used to calculate one set of accident scenarios within a few seconds, and related diagrams are promptly displayed.

In the previous analysis of Unit 1 [HTC Rep.26.1 2013/02/10], [9], we constructed an accident scenario where IC-A was functional after the tsunami attack, and a small leak through a rupture with the equivalent

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diameter of d_{RPV} = 0.86cm occurred immediately after the earthquake.

The NRA analyzed the pressure data from the PCV before the tsunami attack and concluded that the RPV leak did not occur because of the earthquake [11]. We compared the measured data of PCV pressure and the pressure estimation according to the previous accident scenario [9], which assumed an early leakage in the RPV. The previous pressure estimation overestimated the measured data; however, the previous scenario was able describe the rest of the measured pressure data except for the PCV pressure before the tsunami attack.

Based on this finding, we proposed a new accident scenario in which a small leakage occurred at a safety valve (SV) of the RPV at 20:26 on March 11, and a large leakage occurred at 06:20 on March 12 at another SV [HTC Rep.35.1, 2015/03/03]. The other scenario is similar to the previous one [9].

In the accident scenario of the present study, it is assumed that the RPV ruptured at 20:26 on March 11, just before IC-A was restarted at 20:30. According to the previous report [9], the water level was below the TAF, and it is expected that high-temperature vapor accumulated at the top of the RPV because the IC stopped at that time. It is also estimated that the abrupt increase in vapor pressure in the RPV may have caused a vapor ejection through an SV whose operating pressure was higher than the SRVs. The SV ejects the steam directory into the PCV or D/W, whereas SRVs eject the steam to the water in the S/C. This discharge of high-temperature vapor from the SV may cause a failure of the SV and create a continuous leak. We assumed that the leak occurred through a rupture with an approximate diameter d_{RPV} = 1.7 cm to adjust for the measured PCV pressure data.

The remaining aspects of the accident scenario are similar to the previous one [9]. The present accident scenario is as follows:

1. IC-A was operated manually from 18:18 to 18:25 on March 11.
2. A small RPV leak occurred at 20:26. It is suspected that the position of the leak may have been at a SV.
3. IC-A started again at 20:30 according to the original records [26] and Fig. 6. It is estimated to have stopped at approximately 03:00on March 12.
4. The PCV leak occurred at 03:30 in the lower part of the PCV. This caused an increase in the radiation dose at 04:00 at the main gate of the NPP.
5. A large leak from the RPV occurred at 06:20, probably from an SV, and it caused a further increase in the PCV rupture at 06:23.
6. The RPV ruptured again at 16:00 at the bottom of the RPV owing to drying out of the RPV.

The details of the accident scenario are listed in Table 2. It should be noted that the estimated areas where rupture occurred in the PCV between 06:23 and 09:00 on March 12 were adjusted to satisfy the measured pressure data. The assumption of phase equilibrium was not satisfied at that time, because the water level was lower than the TAF and the water vapor was not saturated steam.

The water injection rates to the RPV are smaller than those reported by TEPCO. A recent report by TEPCO mentioned that all injected water may not have reached the RPV because there was a bypass in the injection line. It is also noted that the initial water injection at approximately 04:00 on March 12, 2011, may not have reached the RPV because the pressure was too high. According to the analysis of the water level meter [HTC Rep.32.2, 2014/03/05], the water injection quantities listed in Table 1 are smaller than the values reported by TEPCO.

Table 2: List of events that occurred in the accident scenario of Unit 1. The facts with (*) indicate the estimation in the present scenario

Time	Time after Scram	Facts	Scenario Parameters
March 11 14:46	0	Earthquake, Succeeded in Scram	
14:52	0:06	IC-A,IC-B Auto Start	
14:52	0:06	Simulation Start *	
15:02	0:16	IC-A,B Manual Stop	
15:16	0:30	IC-A Manual Start	
15:18	0:32	IC-A Manual Stop	
15:22	0:36	IC-A Manual Start	
15:25	0:39	IC-A Manual Stop	
15:31	0:45	IC-A Manual Start	
15:34	0:48	IC-A Manual Stop	
15:36:59	0:59:59	Tsunami Attack, AC Blackout	
15:50	1:04	DC Blackout	
15:59	1:13	SRV Blow*	

18:18	3:24	IC-A Manual Start, Vapor Emission from IC was Observed	
18:25	3:39	IC-A Manual Stop	
19:12	4:26	SRV Blow*	
19:30	4:44	Water Level at TAF*	
20:07	5:21	RPV Pressure 6.7 -7.3 MPa	
20:26	5:40	Small Leakage in RPV from SV*	$d_{RPV} = 1.7$ cm
20:30	5:44	IC-A Start	
21:30	6:44	RPV Pressure-decreasing Vapor Emission from IC was Observed	
21:51	7:05	Off-limit R/B due to Radiation Dose Increase	
March 12 0:30	9:44	Injection of Water to IC-A Reservoir	
2:45	11:59	RPV Pressure 0.901MPa	
3:00	12:14	IC-A Stop*	
3:30	12:44	PCV Rupture*	$d_{PCV} = 3.5$ cm
4:00	13:14	PCV Rupture Change*	$d_{PCV} = 3.7$ cm
4:15	13:29	Injection of Water to IC-A Reservoir Stop	
6:00	15:14	PCV Rupture Change*	$d_{PCV} = 3.3$ cm
6:20	15:34	RPV Rupture*	$d_{RPV} = 7$ cm
6:23	15:37	PCV Rupture Increase*	$d_{PCV} = 15$ cm
6:26	15:40	PCV Rupture Change*	$d_{PCV} = 14.7$ cm
6:40	15:54	PCV Rupture Change*	$d_{PCV} = 12$ cm
6:52	16:06	Water Level BAF*	
7:10	16:24	PCV Rupture Change*	$d_{PCV} = 9.8$ cm
8:00	17:41	Water Injection to PRV Start*	$\dot{m}_{inj} = 0.5$ kg/s
8:05	17:19	PCV Rupture Change*	$d_{PCV} = 7.7$ cm
9:00	18:14	PCV Rupture Change*	$d_{PCV} = 7.9$ cm
10:16	19:30	D/W Vent Open	$d_{PCV} = 9$ cm
10:25	19:39	D/W Vent Close	$d_{PCV} = 7.7$ cm
14:26	23:40	D/W Vent Open	$d_{PCV} = 10.4$ cm
14:50	24:04	Water Injection to RPV Stop	$\dot{m}_{inj} = 0$
15:20	24:34	D/W Vent Close*	$d_{PCV} = 8$ cm
15:36	24:50	R/B Hydrogen Explosion	
16:00	25:14	RPV Rupture Area Increase*	$d_{RPV} = 10$ cm
19:04	28:18	Sea Water Injection to RPV Start	$\dot{m}_{inj} = 2$ kg/s
21:45	30:59	Sea Water Injection to RPV Stop	$\dot{m}_{inj} = 0$
23:50	33:04	Sea Water Injection to RPV Start	$\dot{m}_{inj} = 2$ kg/s
March 13 18:00	51:14	Sea Water Injection to RPV Change	$\dot{m}_{inj} = 2.5$ kg/s
March 14 1:10	58:24	Sea Water Injection to RPV Stop	$\dot{m}_{inj} = 0$
20:00	77:14	Sea Water Injection to RPV Start	$\dot{m}_{inj} = 2$ kg/s

Table 2 lists the actual accident events and the accident scenarios estimated from the limited data and testimonies. At the beginning of the Fukushima Daiichi NPP accident, only limited data were available, and that data were often not very precise. The estimated accident scenario at the early stage of the analysis was significantly different from the truth. The scenario presented by the author in the first stage [HTC Rep. 14.2, 2011/5/11] has undergone multiple changes since March11, 2011.

Incorrect data can be corrected for good reasons to derive a more truthful accident scenario. Furthermore, by considering the new data, such as the progress of the internal investigation in the reactor, it is possible to estimate the accident even closer to the truth. It is possible to derive accident scenarios that are closer to the truth by correcting erroneous data for appropriate reasons.

Nevertheless, there are still several in consistencies and unclear points in the present accident scenario listed in Table 2. For example, the restart time of the IC is assumed to be 20:30, which is one hour earlier than the generally accepted restart time. In addition, the PCV destruction times are complicated in the scenario listed in Table 2; however, the scenario in the previous report is simpler and more consistent with the radiation intensity data. This is because the analytical model used in this study assumes vapor-liquid equilibrium in the RPV and PCV; therefore, transient phenomena cannot be described.

Estimation of the rupture location and time on the RPV and PCV, which will be described in subsequent sections, are not in the realm of speculation. However, it is also true that the accident scenario described in Table 2 can explain many of the measured data and events that occurred so far, as will be explained subsequently.

V. Analysis Model

Figure 9 shows the construction diagram of Unit 1 and its physical model for thermo-fluid analysis of the accident scenario. Figure 9 describes the status of Unit 1 as of 12:00 on March 13, 2011, when the RPV and PCV ruptured; moreover, the explosion due to the accumulation of hydrogen at the top portion of the R/B occurred at 15:36 on March 12.

a) *Analysis Model of RPV and PCV*

The physical model in Fig. 9 is simplified to a thermodynamic model, as shown in Fig. 10. The RPV and PCV are simplified vessels that contain vapor and liquid water at saturation conditions. The thermodynamic model of the saturation conditions is similar to the previous models [8], [9]. This model is based on the conservation of mass and energy in the vessels, and the assumption of the phase equilibrium of water and vapor in the vessels. Details of the model were described in the previous report [8].

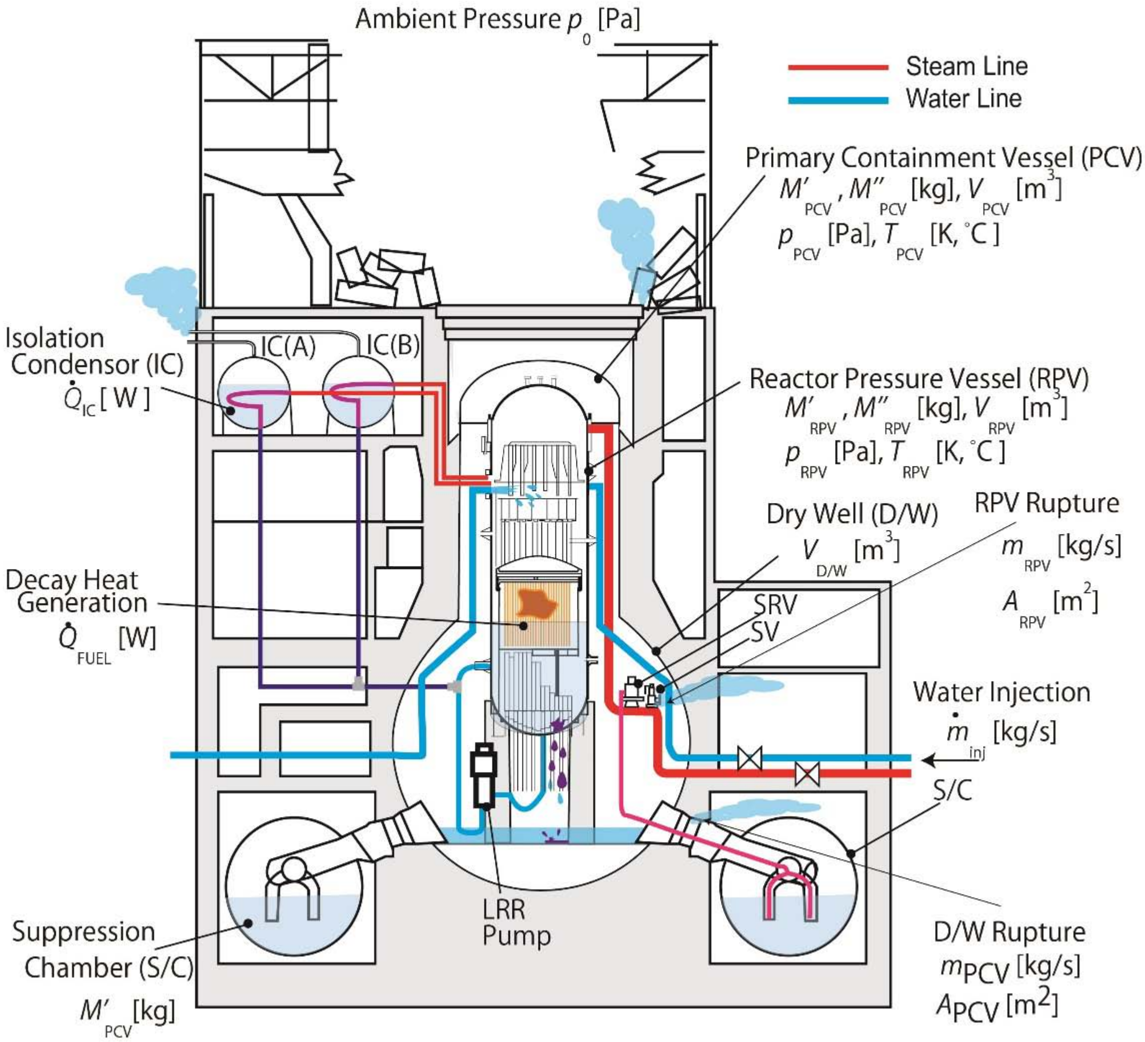

Fig. 9: Physical model of Unit 1 as of March 13, 2011 at 12:00 [9]

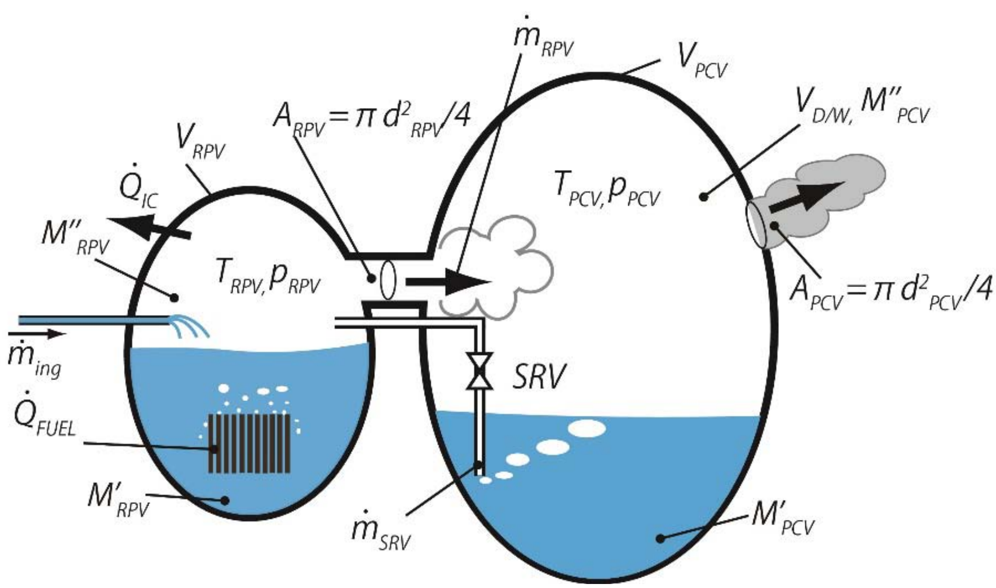

Fig. 10: Phase-equilibrium thermodynamic model of RPV and PCV

Water injection to the RPV, vapor leakage from the RPV to PCV, vapor ejection to the S/C, decay heat, and cooling rate of the ICs are denoted as $\dot{m}_{inj}$, $\dot{m}_{RPV}$, $\dot{m}_{SRV}$ [kg/s] $\dot{Q}_{FUEL}$, $\dot{Q}_{IC}$ [W] respectively.

The differential temperature changes in the RPV and PCV are expressed as follows, assuming the phase equilibrium between the water and the vapor [8].

$$\mathrm{d}T_{RPV}=\frac{\left[-(\dot{m}_{RPV}+\dot{m}_{SRV})(h''_{RPV}-h'_{RPV})+\dot{m}_{inj}(h'_{inj}-h'_{RPV})+\dot{Q}_{FUEL}-\dot{Q}_{IC}\right]\mathrm{d}t}{\left[M''_{RPV}(c''_{p,RPV}+\frac{(h''_{RPV}-h'_{RPV})^2}{p_{RPV}T_{RPV}v''_{RPV}})+c'_{p,RPV}\left[M'_{RPV}+(-\dot{m}_{RPV}-\dot{m}_{SRV}+\dot{m}_{inj})\mathrm{d}t\right]-\frac{V_{RPV}(h''_{RPV}-h'_{RPV})}{T_{RPV}v''_{RPV}}\right]} \tag{1}$$

$$\mathrm{d}T_{PCV}=\frac{\left[(\dot{m}_{RPV}+\dot{m}_{SRV})(h''_{RPV}-h'_{PCV})-\dot{m}_{PCV}(h''_{PCV}-h'_{PCV})\right]\mathrm{d}t}{\left[M''_{PCV}(c''_{p,PCV}+\frac{(h''_{PCV}-h'_{PCV})^2}{p_{PCV}T_{PCV}v''_{PCV}})+c'_{p,PCV}\left[M'_{PCV}+(\dot{m}_{RPV}+\dot{m}_{SRV}-\dot{m}_{PCV})\mathrm{d}t\right]-\frac{V_{PCV}(h''_{PCV}-h'_{PCV})}{T_{PCV}v''_{PCV}}\right]} \tag{2}$$

Here, *h, v, and* c_p represent the enthalpy, specific volume, and specific heat at constant pressure, respectively. The notations "'" and """express the states of water and vapor at the equilibrium condition, respectively. The model assumes that the temperature in the RPV and PCV is uniform. Hence, this model cannot describe the phenomena when the water level is below the TAF and the vessel is filled with superheated vapor.

As shown in the previous report [7], the time history of the decay heat in Unit 1 can be estimated relatively accurately. Because the decay heat is released from the ruptured vessel as steam, the mass flow rate of the steam can be estimated. Assuming the rupture cross section, the pressure difference between the inside and outside of the vessel can be estimated using Bernoulli's equation. Thus, the relationship between the steam flow rate, fracture aperture area, and pressure difference inside and outside the vessel is expressed by the following equation [27]:

$$\dot{m}=CA\sqrt{2\rho_1(p_0-p_1)}\,, \tag{3}$$

where p_0[Pa] is the pressure inside the vessel, p_1[Pa] is the pressure outside the vessel, and ρ_1[kg/m^3] is the density at the minimum cross-sectional area of the mass flow. The flow coefficient of the orifice *C* was set to 0.60 for the inlet orifice.

When the pressure difference becomes large, the flow rate through the vessel opening reaches the speed of sound. The flow rate at that time is expressed by the following equation [24]:

$$\dot{m}=CA\rho^*a^*=CA\rho_0\left(\frac{2}{\kappa+1}\right)^{(\frac{1}{\kappa-1})}a_0\left(\frac{2}{\kappa+1}\right)^{(\frac{1}{2})}=C\left(\frac{2}{\kappa+1}\right)^{(\frac{1}{\kappa-1}+\frac{1}{2})}A\rho_0a_0,\quad \text{for}\quad \frac{p_1}{p_o}<\left(\frac{2}{\kappa+1}\right)^{(\frac{\kappa}{\kappa-1})}\,, \tag{4}$$

where *a*[m/s] is the speed of sound, κ is the specific heat ratio of the vapor, and a value of 1.34 for saturated vapor at 100°C was used as an approximation. The subscript 0 indicates the value in the vessel, and * indicates the state at the velocity of sound. The flow coefficient of the orifice was assumed to be the same as that of a subsonic orifice at the speed of sound. These equations can be used to estimate the steam flow from the RPV to the PCV or from the PCV to the external environment.

When the RPV ruptures and the vapor is ejected to the vapor-phase space of the PCV or D/W, the temperature varies between the D/W and the S/C. In this case, the vapor in the RPV is ejected to the PCV in the adiabatic condition. Using the adiabatic expansion model adopted in a previous report [7], [9], the pressure and temperature changes in differential time *dt* is expressed as follows.

$$\mathrm{d}V_{D/W}=\{(\dot{m}_{RPV}v''_{RPV})(p_{RPV}/p_{D/W})^{1/\kappa}-(\dot{m}_{PCV}v_{PCV})\}\mathrm{d}t \tag{5}$$

$$\mathrm{d}h''_{D/W}=\frac{M_{D/W}h''_{D/W}+(\dot{m}_{RPV}h''_{RPV}-\dot{m}_{PCV}h''_{D/W})\mathrm{d}t}{M_{D/W}+(\dot{m}_{RPV}-\dot{m}_{PCV})\mathrm{d}t}-h''_{D/W} \tag{6}$$

$$\frac{T_{D/W}+\mathrm{d}T_{D/W}}{T_{D/W}+\mathrm{d}h''_{D/W}/c_p}=\left[\frac{V_{D/W}+\mathrm{d}V_{D/W}}{V_{D/W}}\right]^{\kappa-1} \tag{7}$$

$$\frac{p_{D/W}+\mathrm{d}p_{D/W}}{p_{D/W}}=\left[\frac{V_{D/W}+\mathrm{d}V_{D/W}}{V_{D/W}}\right]^{\kappa} \tag{8}$$

Where, the notations follow the ones in Fig. 10. Note that the analysis according to the adiabatic expansion model does not give anaccurate estimation when the water level is below the TAF, and the RPV is filled with superheated vapor. This is because the present model assumes that the ejected vapor is at the saturation condition.

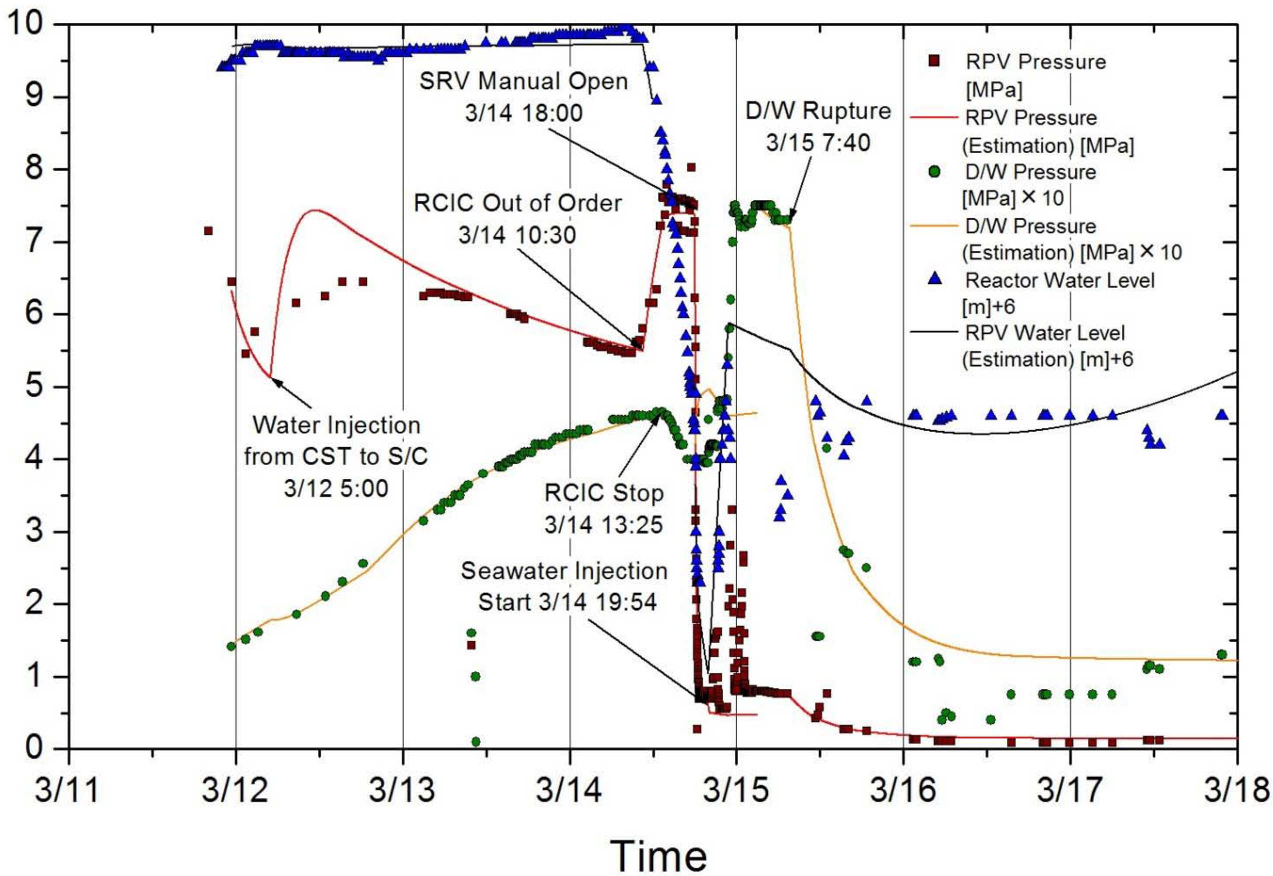

Fig. 11: Comparison with measured plant parameters of Unit 2 and analysis using the thermodynamic model [8]

To demonstrate the accuracy of the present thermodynamic model when compared to measured data of the accident, a comparison of the present analysis with the measured data of Unit 2 is shown in Fig. 11. Our accident scenario of Unit 2 [8] is similar to that of TEPCO. And our analysis result shows better agreement than that of TEPCO.

TEPCO used a large computer simulation code called MAAP. It is a large simulation program to analyze the transient phenomena during a nuclear plant accident; however, it requires a long time to simulate an accident scenario. The present simulation can be conducted using Microsoft Excel, and it requires only a few seconds to simulate one accident scenario. The program can also express appropriate diagrams, as shown in Fig. 11, to examine the analysis results. Accordingly, our simulation program can provide a large number of accident scenarios to obtain good agreement with the data measured during the accident.

b) Analysis of Reactor Water Level Meter

TEPCO constructed a scenario of IC shutdown and early meltdown of the reactor core, claiming that the indicated value of the water level meter in Unit 1 is completely unreliable [6]. The Government Accident Independent Investigation Commission [4] also qualitatively stated the reasons why the water level gauges were not working properly based on the report by TEPCO [6]. However, they did not quantitatively evaluate the readings of the water level meters at that time, and stated that the indicated values of the water level meters were completely wrong. The later report submitted by TEPCO [16] suggests that the indicated values of the water level meters at that time may have contained some information.

We used the model illustrated in Fig. 5, and try to reproduce the water level meter measurements, as shown in Fig. 8. As described in Section III a, the water level meter gives the correct value when the water level

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in the RPV is higher than the TAF because of the structure of the reference condensing water chamber. The reference water level Z_{Ref} is L_1, as shown in Fig. 5, when Z_F is above the TAF. When the water level Z_F is lower than the TAF, the relationship between the apparent water level Z_{Level} and the actual water level Z_F is expressed by the following equation.

$$Z_{Level} = Z_F - Z_{Ref} + L_1 \tag{9}$$

When boiling occurs in the fuel assembly, the water head of the fuel assembly H_F and the apparent water level H_W may be different. Thus, when water boils in the vertical channel, the apparent water level H_W increases owing to the bubbles. Even if the water level H_F falls below the TAF level, the reference water level Z_{Ref} is considered to maintain the reference level of L_1=5.11 m as long as the apparent water level H_W in the fuel assembly channel reaches the TAF, as shown in Fig. 5.

When the water level in the channel drops below the TAF, the reference water level Z_{Ref} in the reference pipe starts to decrease. The speed of the water level reduction depends on the temperature distribution in the RPV and the pipeline layout. In this study, it is assumed that the reference surface water level Z_{Ref} decreases at the same rate as the RPV water level Z_F decreases. It is also assumed that once the reference surface water level decreases, it will not return to the original level owing to the vertical temperature distribution in the RPV. In addition, it is assumed that the lowered reference water level will be maintained while the IC is in operation.

It was assumed that for the water level meter of system B, the water level at the reference surface was suspended at 3.0 m above the TAF when the IC was restarted at 20:30, and the water level remained unchanged until the IC was stopped at 3:00. At the water level meter in system A, the reference surface water level dropped again at 23:30 and reached 2.5 m above the TAF, and then the water level remained constant until the IC stopped.

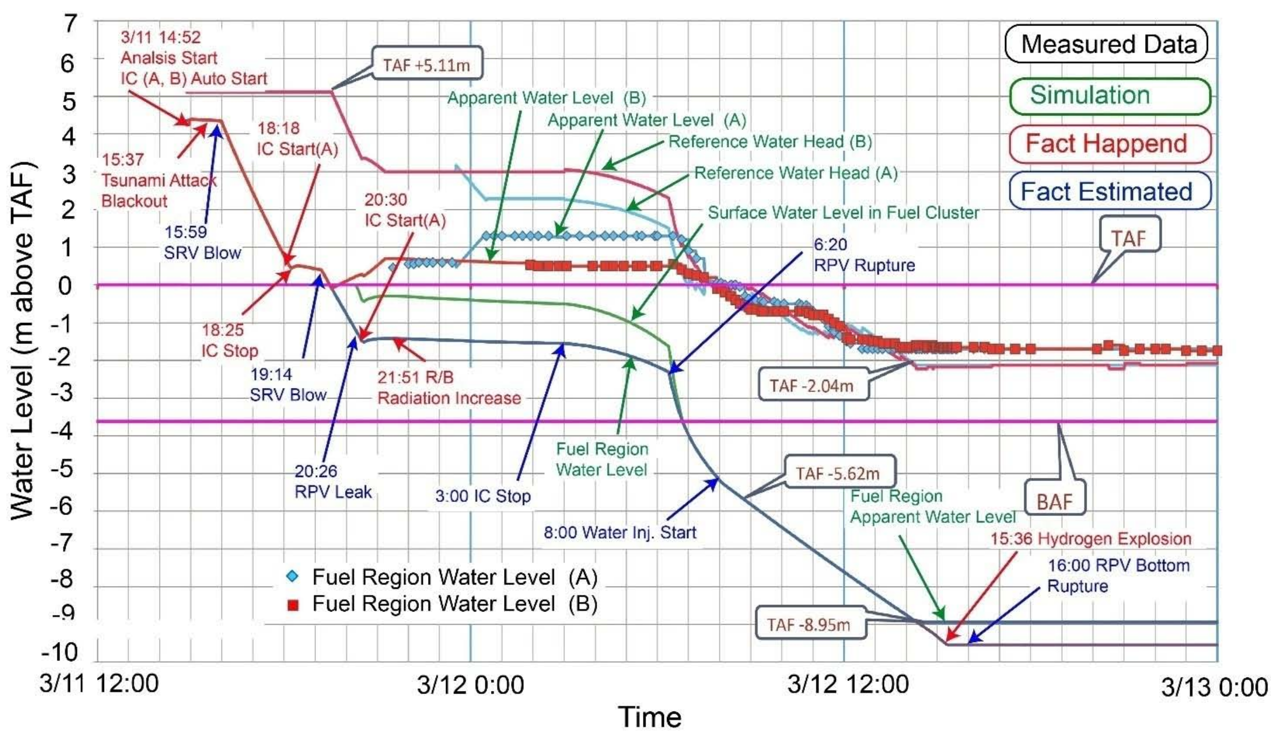

Fig. 12: Reproduction of water level data in RPV using the estimated water level with the accident scenario in the present report

To validate the above-mentioned analysis model and the assumptions, a comparison of the measured water level and our analysis is shown in Fig.12. The calculated reactor water level was obtained from the thermodynamic model using the accident scenario listed in Table 2.

With the above-mentioned assumptions, the water level meter indication at the accident can be reproduced. However, the validity of the speed at which the water level lowered in the reference level meter when the water level fell below the TAF is not clear; however, the above-mentioned assumptions can explain the data obtained from the water level meters at that time. TEPCO reported that there is horizontal piping of the reference level meter, and that system B is approximately 3 m longer than system A. At this stage, the details of the water level piping have not been disclosed. If there is a type of horizontal piping, such as a piping around TAF +3.0m and TAF +2.5m, this hypothesis can be proven. At present, as the location of the piping is unknown, this assessment is only a speculation.

After the IC was shut down at 03:00 on March 12 the reference water level was assumed to decrease at the same rate as the water level in the RPV. When the RPV ruptured at 06:20 and the pressure decreased rapidly, the reactor water level decreased rapidly. The present estimation with these assumptions describes the measured water level after the RPV rupture.

As shown in Fig. 5, when the reference water level is below TAF -2.04 m, the water level in the pipe Z_{Ref} does not decrease anymore because the pipe goes outside the PCV. Further, the apparent water level in the fuel region Z_F does not decrease because the pipes of the water level in the RPV also go out of the PCV at TAF -8.94 m. Therefore, the apparent water level Z_{Level} becomes constant after 14:20. This estimation is in good agreement with the measured apparent water level.

TEPCO attempted to reproduce the measurement of reactor water level meters and claimed that they succeeded in reproducing the data with the accident scenario simulated by TEPCO [16] in the attachments 1-6. The scenario simulated by TEPCO assumed that the water level became the BAF at 19:40 on March 11, which is significantly earlier than our estimation. When we examined the data in the attachment 1-6 [16], the "calculated variable leg water level above PCV penetration" in the attachment could not be understood. TEPCO did not explain the calculation procedure.

VI. Results and Discussion

a) Pressures in PCV

Figure 13 shows the pressure simulations in the RPV and PCV according to the present accident scenario, which is listed in Table 2. The measured data of pressure in the D/W, S/C, and RPV, as shown in Fig. 8, were compared with the present simulation. The radiation dose at the main gate of the NPP is also depicted in Fig. 13.

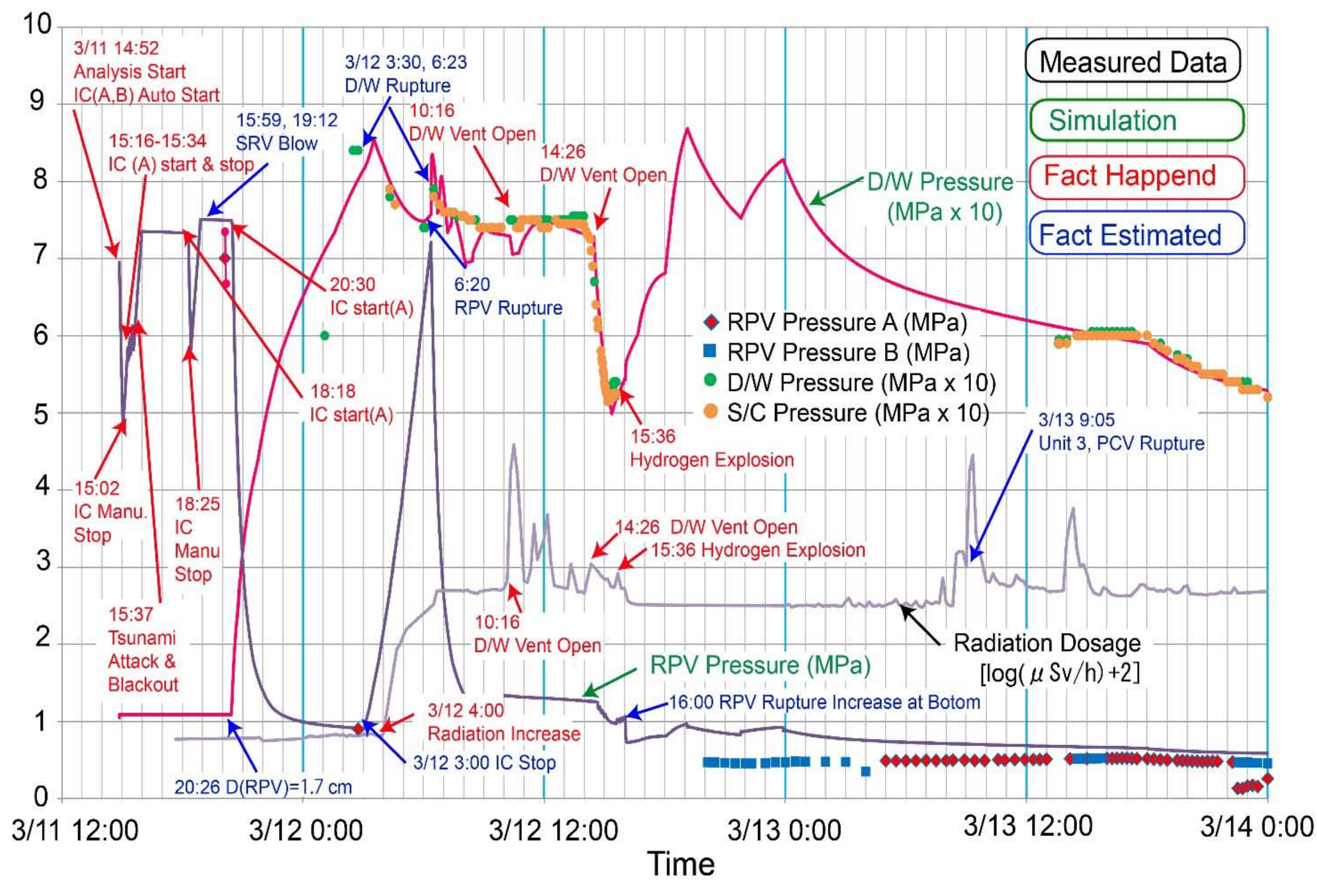

Fig. 13: Measured and estimated vessel pressures according to the present accident scenario. This simulation assumes that the IC was operating until 03:00 on March 12. We assume that a small leak from the RPV occurred at 20:26 on March 11, the PCV ruptured at 03:30 on March 12, and the ruptured area of the PCV increased at 06:23; the RPV ruptured in the vapor phase at 6:20. The RPV ruptured again at the bottom portion at approximately at 16:00.

The pressure estimation of the PCV, i.e., the S/C and D/W, agrees well with the measured data, except for the measurement at 01:05 on March 12. This datum did not appear in the original data reported at that time [26]. The areas where rupture occurred in the PCV from 06:23 to 09:00 on March 12 were set to satisfy the measured data, because the assumption of phase equilibrium is not satisfied when the water level is lower than the TAF. Furthermore, superheated vapor was ejected from the RPV to D/W at that time.

We suspect that when the water level became lower than the TAF at 20:26 on March 11, the temperature of the steam increased and the zirconium sheath of the fuel rods reacted with the high-temperature steam, resulting in the generation of high-temperature hydrogen gas. This high-temperature steam and hydrogen gas may leak from the RPV; consequently, the pressure in the PCV starts to increase. In the present accident scenario, we assumed that the RPV had a small leak at 20:26.

This accident scenario explains that the reason for the increase in the radiation level in the R/B at 21:51, because the leaked contaminated gas from the RPV was stored in the PCV, resulting in an increase in the radiation in the R/B at that time. Then, the PCV ruptured at around 03:30 on March 12 owing to the high pressure. At this stage, the IC had stopped, and the water level was lower than that at 20:26 on March 11. The ruptured area was estimated to be of an equivalent diameter of $d_{RPV} = 1.7\mathrm{cm}$. The ruptured area increased at 06:23 owing to the steam ejection from the RPV that ruptured at 06:20. The real rupture area of the PCV cannot be estimated because the superheated vapor cannot be estimated using Eqs. (4) and (5). When water was injected into the RPV, the ejected steam became saturated again. According to the estimation at 08:00, the rupture diameter was approximately 8 cm, which is in good agreement with our early estimation [9].

The pressure after 10:26 decreased owing to the venting of the PCV. As listed in Table 2, the apparent rupture area increased owing to the vent motion of the PCV and the area returned to the previous value when the venting valve was closed. Note that the rupture area did not change with the hydrogen explosion at 15:36. This indicates that the rupture position was in the lower part of the PCV, as specified by the author [7]. This was also proved by TEPCO [13].

The radiation intensity increased 12 times between 04:00 and 04:40, and it also increased between 05:10 and 06:30. These increases in radiation dose agree with the present estimation of the PCV rupture times of 03:30 and 06:23. The radiation dose increased in the R/B at 21:51on March 11; consequently, entering the building was prohibited. The radiation dose at the main gate did not increase at that time, as shown in Fig. 13. This implies that the contaminated gases that leaked from the RPV at 20:26 into the PCV may not have leaked into the environment. The water level of the RPV was under the TAF from the present estimation, and the contaminated vapor in the RPV may have leaked to the PCV after 20:26.

b) Pressure Values in RPV

The pressure estimation of the RPV by the present accident scenario is also shown in Fig. 13. This estimation assumes that IC-A was working between the times of 18:18 and 18:25. It also assumes that the IC was restarted at 20:30 according to the original data presented by TEPCO [26] and as shown in Fig. 6. This analysis assumes that the IC was nonfunctional at approximately 03:00 on March 11.It is suspected that the hydrogen produced by the zirconium–water-vapor reaction accumulated in the RPV, and the accumulated gas stopped the condensation of vapor in the IC.

This estimation of the time at which the IC stopped functioning is significantly later than that estimated by TEPCO [16]. The report published by TEPCO states that "When compared with the progression in the IC continuous operation after 18:25, the continued IC operation delayed the RPV damage and let to less erosion of the containment vessel concrete. But in the overall progression of the accident, it would be quite likely that there was only a minor difference from what actually occurred in Unit-1." TEPCO estimated that the IC became nonfunctional because the accumulated hydrogen deteriorated the condensation ability in the IC in the early stage of the accident.

The estimation presented by TEPCO may be possible when the condensation heat transfer in the IC is a natural convection type of heat transfer such as the condenser in Fig. 1. The condenser in the power plant condenses the vapor outside the heat transfer pipe and cooling water is circulated in the pipe. However, in the case of the IC, the condensing steam flows in the pipe, and the cooling water is boiling outside the pipe. As shown in Fig. 9, the ICs were placed at high positions. The condensed water in the IC is subjected to a large suction head owing to the large difference in height between the IC and the entrance of the condensed water at the RPV. In this case, we consider that the forced convection condensation may have continued after the generation of hydrogen gas. Hence, we estimated that the IC became nonfunctional at approximately 03:00 on March 12.

According to the discussion in a previous report [9], the cooling performance of the IC was significantly greater than the decay heat generated when the operators restarted IC-A at 18:18, which was 3.5 h after the scram. The pressure quickly decreased after the restart of the IC. The pressure increased after IC-A stopped manually at 18:25; then, the SRV blew steam to the S/C and the water level in the RPV decreased. We assumed that the IC restarted at 20:30. At that time the water level was below the TAF, as shown in Fig. 12.

It is extrapolated that vapor circulation from the operating IC may have maintained the fuel rods at relatively low temperatures. However, the temperature becomes significantly high when the vapor circulation stops owing to the failure of the IC. According to this discussion, certain fuel rods may have been at a high temperature at 20:26 and the high-temperature vapor would have accumulated at the top of the RPV. It can be expected that the temperature of certain rods increased, and a reaction occurred between the zirconium and the water vapor. This abrupt increase in temperature and the gas generation may have caused a small leak on the RPV at 20:26.

The temperature in the RPV may have decreased after the IC started again at 20:30 and the fuel temperature at TAF may have stayed at a relatively low temperature until the IC stopped at 03:00 on March 12. Then, the pressure and temperature in the RPV increased promptly and the breakdown of the fuel core may have started. In this case, the pressure in the RPV is expected to be significantly higher than that estimated in Fig. 13 because the estimated pressure assumes phase equilibrium of the water vapor.

There are only two pressure values that were measured for the RPV after the tsunami attack and before the hydrogen explosion at 15:36 on March 12. When we examined the pressure data at 20:07 on March 11 the original value was in the range of 6.7-7.3 MPa, as shown in Fig. 13. TEPCO adopted the average value in their reports [16]. The pressure at 02:45 on March 12 was0.901 MPa. TEPCO claimed that this low pressure is an evidence that the IC was not working and the RPV ruptured in the early stage of the accident.

The IC had a sufficiently large cooling performance to cool the decay heat just after the scram. The decay heat at 02:45 was 22% of the value that was estimated immediately after the scram [7]. As shown in Fig. 13, the pressure in the RPV decreased quickly and became the measured pressure at 02:45. Thus, it was determined that this pressure decrease in the RPV could be achieved if the IC was working.

When the IC stopped at 03:00, the pressure increased significantly quickly. We estimated that the RPV fracture occurred at 6:20 owing to the quick increase in the pressure of the RPV. The blow-in gas from the RPV to the PCV caused the pressure to increase at 06:23.

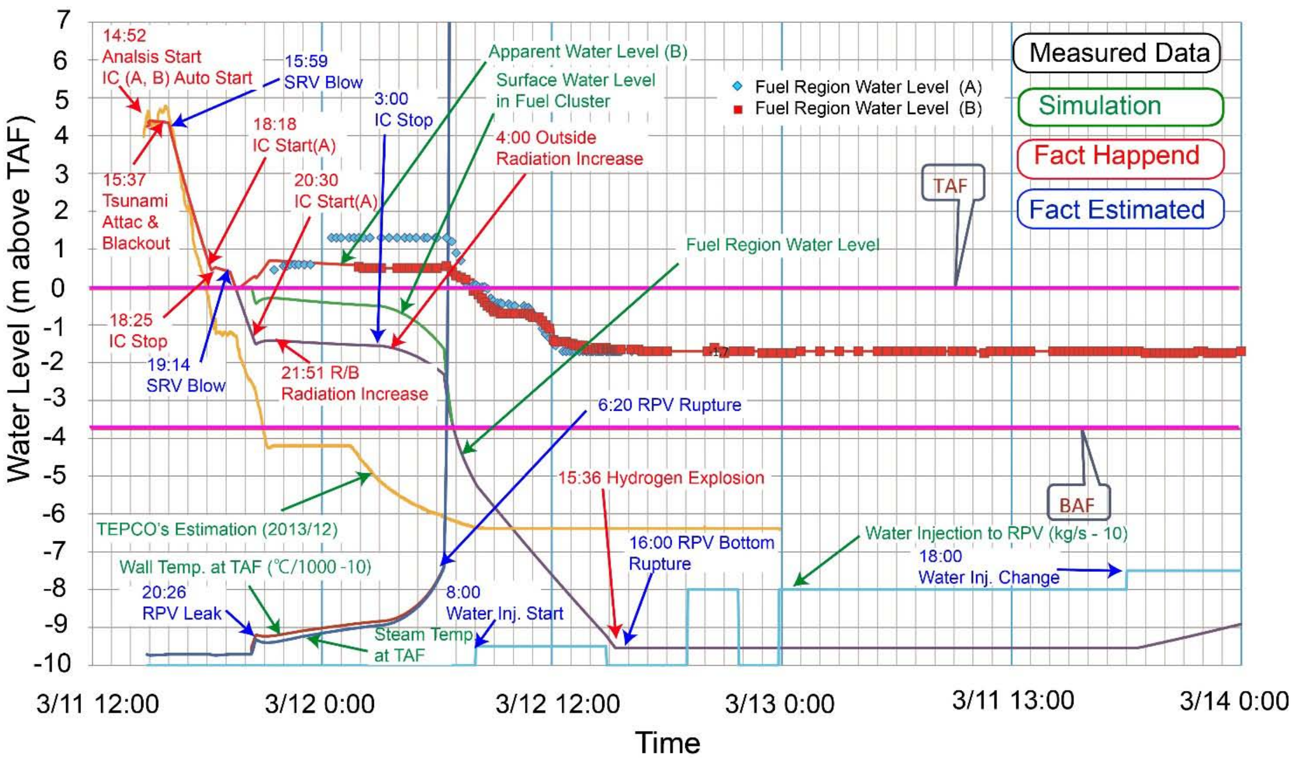

Fig. 14: Estimated water level in the RPV according to the present scenario in comparison with measurements in Fig. 8 and the estimations presented by TEPCO [12]. The present estimation shows the water level was lower than the TAF at 20:26 on 11 March, and a small leakage occurred in the RPV. This explains the radiation increase in the reactor building at 21:51. IC-A was restarted at 20:30, and stopped at 03:00 on March 12. We estimate that the RPV ruptured at 06:20; then, the water level reached the bottom and the fuel leaked out at approximately at 16:00.

c) Water Levels in RPV

Figure 14 shows the estimated water levels and measured data from reactor water level meters A and B. According to heat transfer analysis of fuel clusters, the water level in the fuel cluster is higher than the water level outside the shroud when the water level becomes lower than the TAF [HTC Rep.26.2, 2013/03/03],[9].

The water levels (outside the shroud), as estimated by TEPCO [12], and the estimation that the author derived from the heat transfer model in Section V b and Fig. 12 are also shown in Fig. 14. The upper part of the fuel may have been wet because boiling water inside the fuel cluster expanded owing to the void in the cluster channels. The water level in the cluster channel Z_w is also shown in Fig. 14. This can be estimated by the void fraction distribution or quality distribution in the fuel cluster, assuming the cluster is a single pipe with uniform heat flux, as discussed in a previous report [9].

When the IC restarted, as discussed above, the vapor circulation from the operating IC may have kept the fuel rods at relatively low temperatures, even if the water level Z_W was below the TAF. When the IC stopped, and the water level in the cluster Z_w became lower than the TAF, the fuel surface was covered with pure vapor and the wall temperature increased rapidly. The temperature of the steam and the surface of the fuel rod at the TAF can be estimated by the steam generation rate and forced convection in a pipe [9]. The estimated wall temperatures of the fuel rod and steam at the TAF are shown in Fig. 14.

The estimated rates of water injection to the RPV are shown in Fig. 14. The injection rates are smaller than the reported values, because there is a possibility that the injected water entered the bypass line, and all water may not reach the RPV. The injection rate was adjusted to satisfy the condition that the reconstructed water level meters in Fig. 12 agree with the obtained data [HTC Rep.26.2, 2013/03/03].

In the present estimation, the water level started to decrease at 15:59 on March 11 as the RPV steam was blown down to the S/C by the SRVs. This behavior agrees with the measured data [13]. The decrease in water level stopped when the operators restarted the IC at 18:18. Then, the water level started decreasing again at 19:14 because the IC was stopped at 18:25. The water level reached the TAF at 19:30. At that time, the fuel cluster at the TAF was still wet because the bubbly flow in the fuel cluster maintained saturation temperature at the fuel surface.

When the water level was below the TAF at 20:26, the fuel roads at the TAF dried out and high-temperature steam was ejected to the upper part of the RPV. The pressure and temperature of the steam at that time is expected to be significantly higher than the estimation. Moreover, the zirconium–steam reaction may have occurred at that time. It is suspected that the high-temperature steam was ejected through a SV.

When the IC was restarted at 20:30, the water levels in the RPV and fuel cluster were below the TAF. However, it is estimated that the vapor temperature and pressure decreased owing to the circulation of water and vapor through the IC. When the IC was working, stable circulation was maintained until the IC stopped again. This stable water level indicates satisfactory operation of the water level meters, and the measured water level data can be reconstructed as shown in Fig. 12.

TEPCO [12] carried out a simulation of the accident at Unit 1 using the simulation program MAAP. TEPCO estimated an early meltdown due to the nonfunctional IC after the tsunami attack. We performed a simulation based on the same accident scenario that was adopted by TEPCO [9] and obtained approximately identical results for the water level in the RPV as obtained by MAAP. However, the water level estimation by TEPCO [12] could not reconstruct the measured water level data [HTC Rep.32.2, 2014/03/05].

We estimated that the IC stopped at approximately 03:00 on March 12. Then, the temperature of the fuel increased rapidly, as shown in Fig. 14, and the meltdown started. The water level in the RPV decreased quickly because of decompression boiling due to the abrupt pressure decrease at 06:20. The RPV ruptured owing to the high pressure and high temperature of vapor in the upper part of the RPV at 06:20. The vapor ejected to the PCV caused a rapid increase in the size of the ruptured area of the PCV at 06:23. It should be noted that the present thermodynamic model cannot accurately express the behavior of the RPV when the water level is below the TAF. However, the phenomena that occurred can be qualitatively described by adjusting parameters such as the rupture area.

As the pressure in the RPV decreased, water injection started at 08:00, as shown in Fig. 14. At that time, we considered that the thermodynamic equilibrium was somehow maintained owing to the injection of water. The injection rates were smaller than the reported values, because there is a possibility that the injected water entered the bypass line and the entire amount of water may not reach the RPV. The injection rate was adjusted to satisfy the condition that the reconstructed water level meters in Fig. 12 agree with the obtained data.

The reactor water level decreased after the RPV ruptured at 06:20, and it became almost zero at approximately 16:00. The present accident scenario estimated that the RPV ruptured again at that time. TEPCO estimated that the RPV melted down around 22:00 on March 11. This is significantly earlier than our estimation at around 16:00 on March 12. The molten fuel may have spilled out from the bottom of the RPV; however, this scenario estimates that a large portion of

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the fuel remains in the RPV to date. The reasons for this estimation are discussed in the subsequent section.

VII. Prediction of Rupture Times and Positions

From the previous discussion, it is possible to explain the measurement data, activity records, and eyewitness testimonies of the workers at that time, if the IC is assumed to be working for a certain period of time after the tsunami attack. The accident scenario listed in Table 2 can explain, to some extent, the pressure data, water levels, and radiation intensities of the RPV and PCV, which were measured at the time of the accident.

We estimated that at 20:26 on March 11, a crack with an equivalent diameter of 1.7 cm occurred in the RPV and steam was ejected into the D/W. At 03:30 on March 12, the PCV was damaged and its equivalent diameter was 3.5-3.7 cm. At 06:20, the RPV was damaged and a large amount of steam was ejected into the D/W. The equivalent diameter of the damaged part of the RPV was 7 cm. The water in the RPV ran out and the molten fuel leaked from the bottom of the RPV into the pedestal of the PCV at approximately at 16:00. The time of fuel leakage was significantly later than that presented in the evaluation by TEPCO, and we estimated that a significant fraction of the fuel remained in the RPV. Subsequently, when the water injection stabilized, the cracks at the bottom of the RPV were blocked by water and molten fuel, and steam continued to leak from the cracks at the upper part of the RPV.

We estimated the location of the rupture on the PCV [HTC Rep.25.1, 2012/12/26], [9], and we presumed that the location of the rupture was at the bellows that connects the D/W and the S/C. TEPCO examined the interior of the R/B and estimated that the rupture occurred at the bellows near the bottom of the D/W and vacuum breaker tube [13]. This position is considerably close to our estimated position [HTC Rep.25.1, 2012/12/26].

Between March 20 and 22, 2011, there was a period of time when the water injection rate into Unit 1 was significantly low. This decrease in water injection resulted in the temperature of the entire reactor reaching approximately 400°C. After March 23, the water injection volume increased and the temperature inside the reactor rapidly dropped. Electric power was restored to the central control room after March 20, and temperature data from various parts of the reactor was finally obtained.

By examining the temperature data of each part of the reactor, it is possible to estimate the condition of the reactor after the accident and the damaged parts to a certain extent. However, the exact locations of the temperature sensors and the reactor components are not known at this time. It is important to understand that there are a number of uncertainty factors involved in such estimations. This analysis is based on public data; however, it is expected that there are several unpublished reports that are not available to the author. It is possible that the present estimation may not be accurate when those data become available.

In this section, the author attempts to present bold predictions regarding the positions and times of vessel ruptures according to the present accident scenario listed in Table 2. These predictions may change based on different accident scenarios, and the present predictions may not be accurate. However, to contribute to the nuclear reactor accidents in the future, we will attempt to estimate the locations and times of the ruptures in the RPV and PCV without fear of being accused of inaccuracy.

a) *Identification of Temperature Measurement Points*

TEPCO released the temperature measurement data of each part of the reactor after March 20, 2011, and in the Microsoft Excel format on May 17 [29]. Table 3 lists the "List of plant data collected by the operator during the accident" [30] and the locations and names of the temperature data that were measured immediately after the accident, as estimated from various public data. Based on these data, it is possible to estimate the locations and names of the temperature data measured immediately after the accident. The temperature measurement points of each part of the reactor were estimated and are shown in Figs. 15 and 16.

The position of the water supply nozzle is important; however, the exact location is unknown. Further, there is no precise information regarding the location of the temperature sensors of the SV and SRV, and the direction in which the SV blows out the steam. If this information was available, the accuracy of the estimation would increase.

Table 3: List of temperature data collected by the operator during the accident

TC No.	Name	Tag. No	Service Name	Position	Direction	Height
20	Vessel Flange	TE-263-66B1	Vessel Head Flange	RPV	270	33000
21	Vessel Flange(Vessel Stream)	TE-263-67A1	Vessel Stud	RPV	270	33000
22	Water Supply Nozzle N4B (Terminal)	TE-263-69D1	N4B Nozzle End	RPV	135	27750
23	Water Supply Nozzle N4B(Inner)	TE-263-69D2	N4B Nozzle End Inboard	RPV		
24	Water Supply Nozzle N4C(Terminal)	TE-263-69E1	N4C Nozzle End	RPV	225	27750
25	Water Supply Nozzle N4C (Inner)	TE-263-69E2	N4C Nozzle End Inboard	RPV		
26	Vessel Core	TE-263-69F3	Vessel Core	RPV	270	22160
27	RPV Lower Part (Lower Head)	TE-263-69L1 or 69L2	Vessel Bottom Head	RPV	25 or 130	1550
28	Control Rod Drive (CRD) Upper Housing	TE-263-69N1	CRD Housing Top Edge	RPV		
29	CRD Lower Housing	TE-263-69N3	CRD Housing Top Edge	RPV		
30	SV Exhaust 203-4A①	TE-261-13A	SV-4A	PCV（D/W)		
31	SV Exhaust 203-4C②	TE-261-13C	SV-4C	PCV（D/W)		
32	SV Exhaust 203-4B③	TE-261-13B	SV-4B	PCV（D/W)		
33	SRV Exhaust 203-3A⑥	TE-261-14A	RV-203-3A（Blowdown Valve)	PCV（D/W)		
34	SRV Exhaust 203-3B⑦	TE-261-14B	RV-203-3B（Blowdown Valve)	PCV（D/W)		
35	SRV Exhaust 203-3C⑧	TE-261-14B	RV-203-3C（Blowdown Valve)	PCV（D/W)		
36	SRV Exhaust 203-3D⑨	TE-261-14B	RV-203-3D（Blowdown Valve)	PCV（D/W)		
39	HVH-12CReturn	TE-1625C	HVH-12C Return Air	PCV（D/W)		
41	RPV Bellow Seal（HVH-12A 1625L) HVH-12A?	TE-1625A	HVH-12A Return Air	PCV（D/W)		
43	S/C Pool Water			PCV（S/C)		

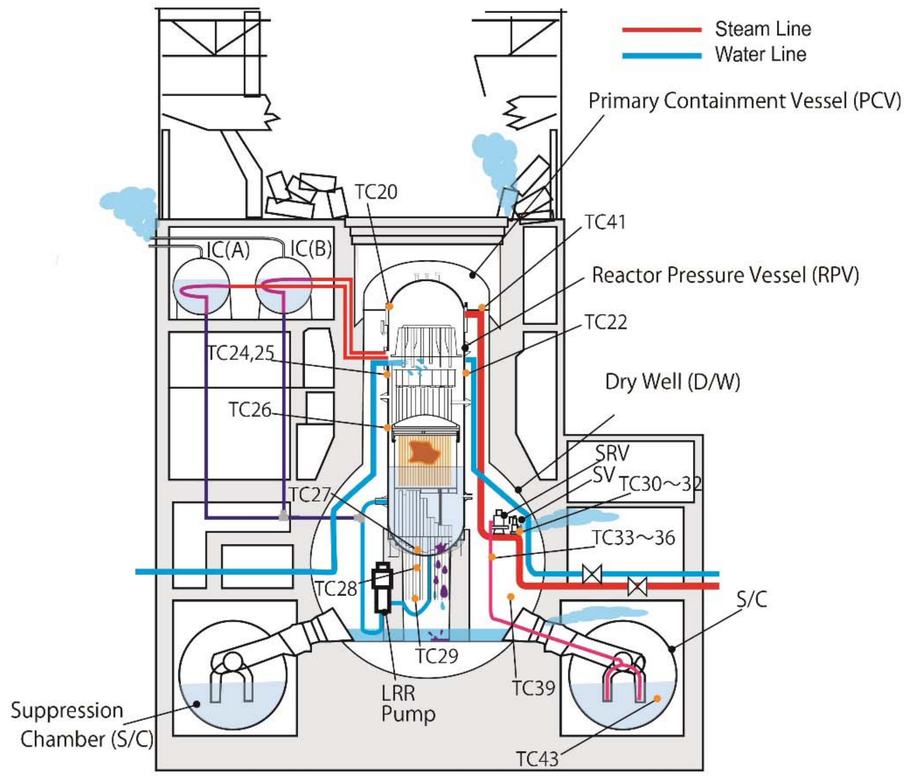
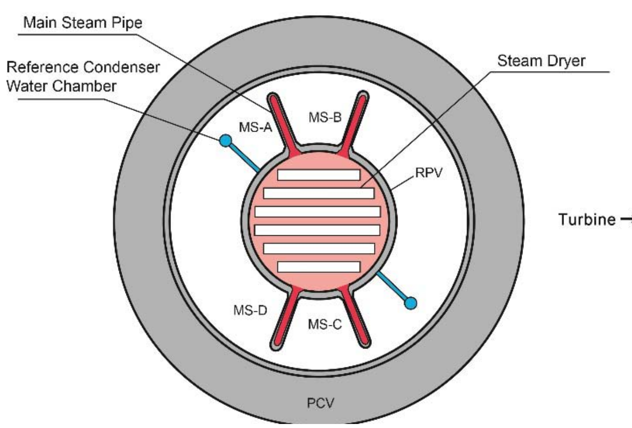
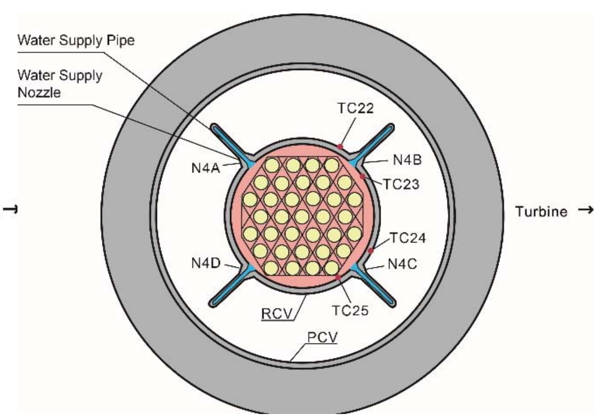


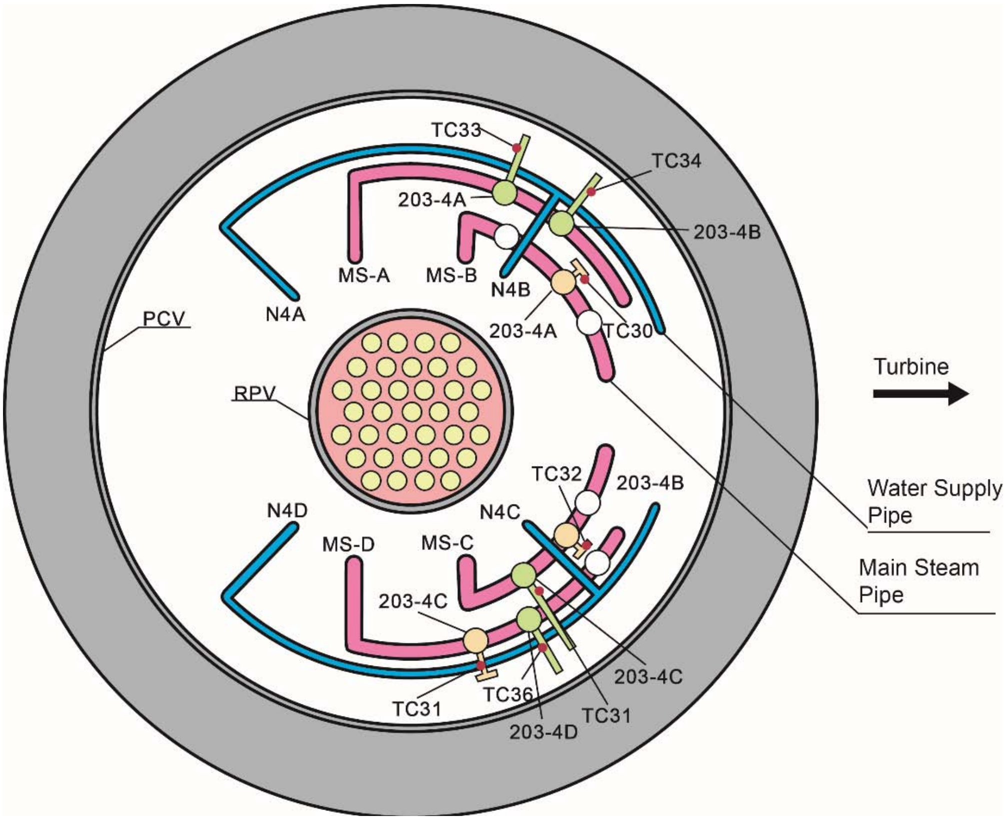
Fig. 15: Cross section of the reactor and estimated location of the position of the thermometer



(a) Reactor core around the main steam pipe
(Cross section at TAF+ 5.64m)



(b) Reactor core around the water supply pipe
(Cross section at TAF -2.18m)



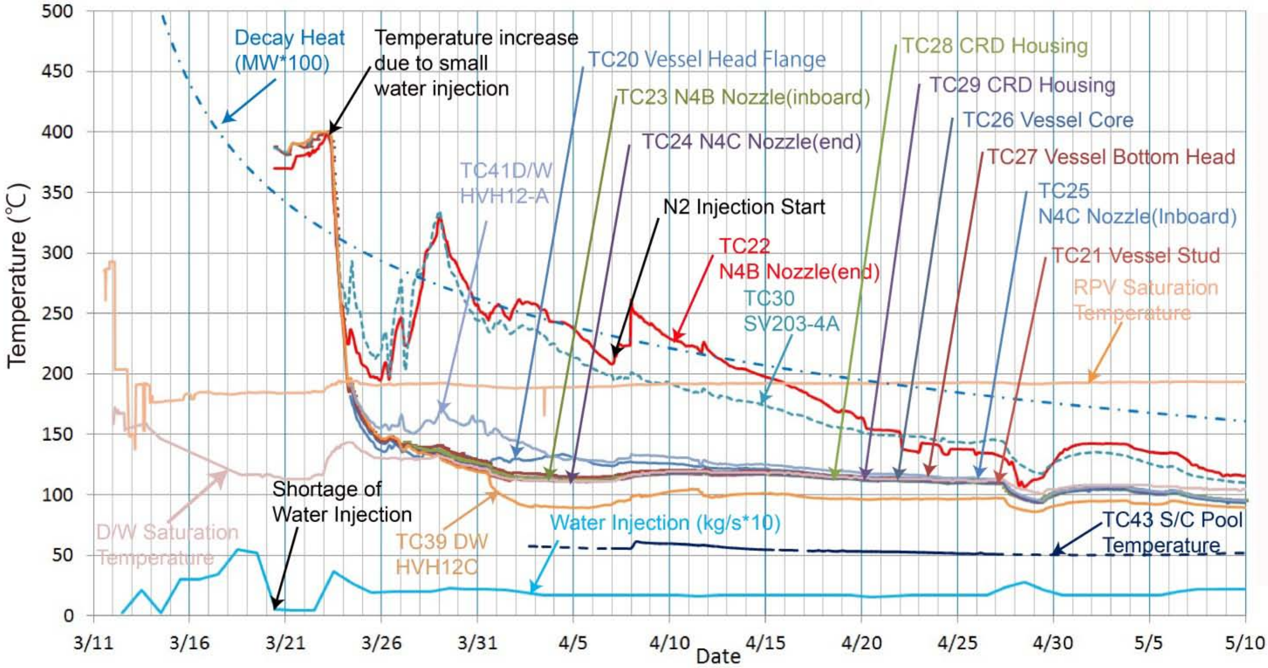
(c) Temperature measurement positions around SV and SRV

Fig. 16: Reactor cross section and estimated temperature measurement points at each height

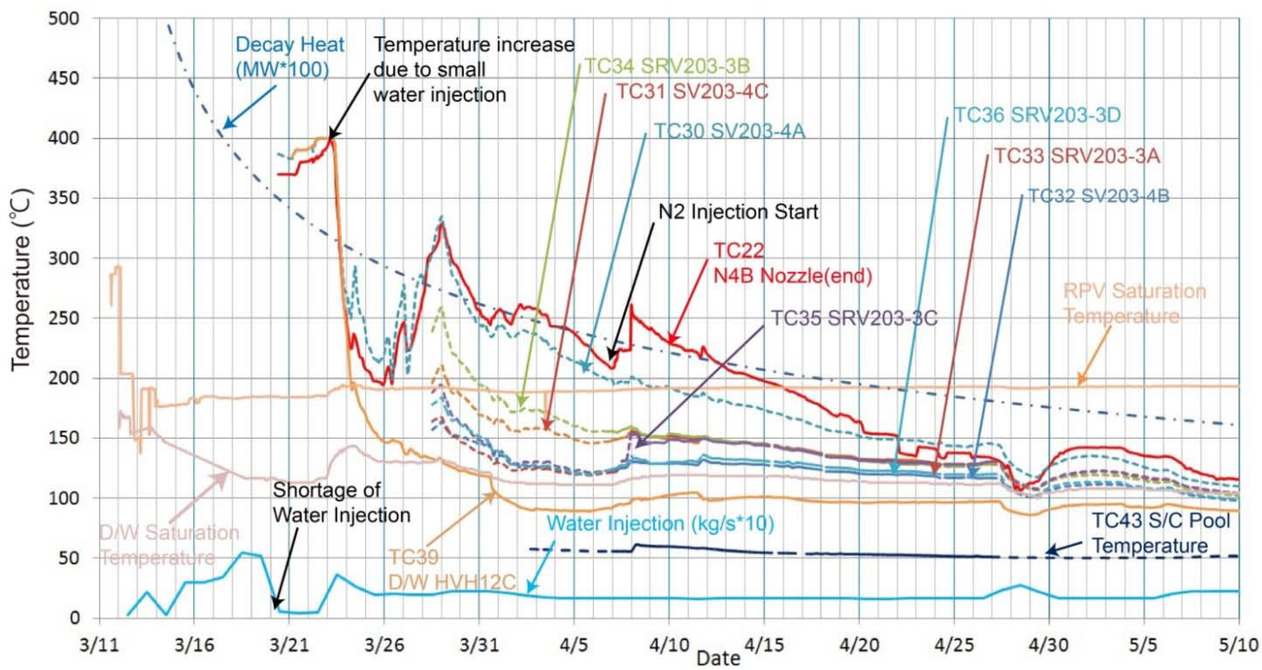
Figures 15 and 16 show the locations of the temperature measurement points in the reactor, as estimated by the author. The exact locations of the temperature measurement points and the details of the reactor structure are not published. The positions of the temperature measurement points in Figs. 15 and 16 were estimated using the data listed in Table 3 and various published data. Therefore, these positions may differ from the actual positions. The numbering of the temperature measurement points shown in Figs. 15 and 16 corresponds to the numbers listed in Table 3.

Figure 16(c) describes the estimated locations of the SRV and SV installed in Unit 1. Both valves were installed on the main steam pipe. The steam released from the SRV was condensed with water in the S/C. However, the steam released from the SV was ejected directly to the D/W. Therefore, the pressure in the PCV may rise rapidly when the SV is activated. The pressure-release setting of the SV is higher than that of the SRV. According to the attachment of the interim report published by TEPCO [31], the working pressure of the SRV ranges from 7.27 to 7.71 MPa, while the working pressure of the SV ranges from 8.51 to 8.62 MPa; consequently, the SV is not activated under normal operating conditions. However, the SV may be activated when the water level in the RPV drops below the TAF and the pressure increases rapidly, as is the case when the steam–zirconium reaction occurs.

b) Evaluation of Temperature Data



(a) Temperature changes around RPV and PCV



(b)Temperature changes around SV and SRV

Fig. 17: Temperature changes in various parts of the reactor, water injection rate, decay heat rate, and saturated steam temperature after March 20, 2011

As mentioned above, the amount of water injected into Unit 1 was significantly reduced from March 20 to 22, and the temperature in various parts of the reactor reached 400°C. Then, the amount of water injected into the reactor core increased, resulting in a rapid decrease in the temperature inside the reactor. Figure 17 shows the temperature changes in each part of the reactor that could be measured after March 20. The temperature measurement points are listed in Table 3 and illustrated in Figs. 15 and 16. The record of water injection volume at that time and the change in decay heat are shown in Fig. 17. The saturated vapor temperatures calculated from the RPV and D/W pressures are also depicted.

Figure 17 shows that the temperature of each part of the reactor increased and became almost uniform owing to the extreme decrease in water injection from March 20 to 22. After the water injection rate was stabilized in April, the temperature of each part of the reactor gradually decreased with the decrease in the decay heat.

First, let us compare the temperature measurement position in Fig. 15 with the temperature change in Fig. 17(a). It should be noted that the temperature at the bottom of the RPV (TC27) decreased simultaneously with the water injection and became equal to the saturation temperature of the D/W. The temperature of the control rod drive housing in the PCV, which is called the control rod drive (CRD), (TC28 and TC29) was also at the saturation temperature of the D/W. Conversely, the end of the water supply nozzle N4B (TC22) and SV 203-4A (TC30) remained hot and their temperatures were higher than the RPV saturation temperature. The end of the feed water nozzle N4C (TC24) was at the same temperature as the bottom of the reactor. This suggests that the water supply was coming from here, and the temperature was low.

Let us assume that most of the fuel rods have melted out of the RPV into the PCV and accumulated in the pedestal at the bottom of the PCV, as TEPCO estimates. Water injection would flow from the feed water nozzles into the RPV and flow out of the bottom of the RPV to cool the fuel deposited in the PCV. Therefore, the temperature of the D/W with the heat source should be higher than the temperature inside the RPV. However, the measurement result indicated the opposite. Furthermore, the temperature inside the D/W (TC39) was lower than the saturation temperature of the D/W. The phenomena estimated by TEPCO is unlikely because the D/W is filled with high-temperature vapor when most of the fuel is discharged into the PCV.

By assuming the accident scenario of this report, as listed in Table 2, the injected water leaked out from the hole at the bottom of the RPV, which was formed at approximately at 16:00 on March 12. Conversely, the superheated steam generated by the fuel in the RPV leaked out from the crack in the gas phase. These phenomena explain the temperature changes shown in Fig. 17(a). The fractures in the RPV were formed at approximately at 10:26 on March 11 and at 06:20 on March 12. As the water injection into the RPV has been stable since March 23, it is presumed that the water that saturated in the RPV leaked out from the lower part of the RPV. The water caused the lower part of the RPV and the D/W of the RPV to have homogeneous temperatures.

Next, the thermometer arrangement in Fig. 16(c) is compared with the reactor temperature data in Fig. 17(b). If the SV (203-4A), which is connected to the main steam pipe of system B, was damaged and continued to discharge steam, it can be explained that the thermometer at the end of the feed water nozzle N4B (TC22) and the temperature data of SV 203-4A (TC30), which is installed near the main steam pipe of system B in the RPV, showed prominently high temperatures.

Conversely, the temperature of the end of the feed water nozzle N4C (TC24) in Fig. 17(a) is cold at the same time, when the water injection restarted. This suggests that water injection to the core was performed through nozzles N4C and N4B immediately after the accident; however, the authors do not have detailed data regarding this. The inner thermometer (TC23) of nozzle N4B is also at a low temperature. As the detailed locations of the thermometers are not known, further investigation is required to determine these phenomena.

While considering the SV and SRV temperatures, SRV203-3B (TC34) near SV203-4A (TC30) showed a high temperature. One possibility is that the steam that leaked from SV203-4A hit the temperature measurement point of SRV203-3B, and TC30recorded a high temperature. Conversely, the high-temperature steam have been released from the SRV to the S/C at approximately 06:20 on March 12. It is also possible that the steam damaged the valve seat of SRV203-3B at that time, and the steam continued to leak from the SRV after March 23.

As for the SVs, SV203-4C (TC31) recorded the second-highest temperature after SV203-4A. If the steam that leaked at 20:26 on March 11was caused by the valve seat damage of this SV, the temperature change of TC31 can be understood. The SRV (SRV203-3B) showed temperatures higher than the saturation temperature of the D/W. It is possible that the valve seat of the SRV was damaged by the hot steam leak at 06:20 on March 12, as shown in Figure 14, and the leak continued.

It will be a long time before the SV and SRV are retrieved and inspected; therefore, this assumption cannot be clarified until further investigations are performed. It may not be possible to ever identify the locations of the RPV leaks.

c) Estimation of Fracture Status based on Temperature Data

In the interim report document presented by TEPCO [31], the operating pressures of the SVs and SRVs are shown; however, the pressure values that are set for the operation of each valve are not stated. Therefore, assuming that the accident scenario in this report is correct, the estimated valves and estimated operating pressures are listed in Table 4. According to this accident scenario and Figure 17(b), the pressures set for the operation of SV203-4C and SV203-4A must be lower than that of SV203-4B for the valve seat of SV203-4C to become stuck at 20:26 on March 11 owing to the high-temperature steam and for SV203-4A to be damaged at 06:20 on March 12.

As mentioned earlier, the seat of the SRV (SRV203-3B) may have also become stuck at this time. The temperature of SRV203-3C increased marginally after the injection of nitrogen; therefore, the operation pressure was estimated to be lower than SRV203-3A and SRV203-3D. If the estimated value and the actual valve setting operating pressure are the same, the accuracy of this accident scenario will increase.

According to the estimation in this report, the SVs may have been activated owing to the rapid pressure increase and dry out of the fuel rods after 20:26 on March 11 and 03:00 on March 12. As shown in Fig. 14, it is presumed that the steam stored in the upper part of the vessel was significantly hot when the RPV was destroyed. At that time, it cannot be excluded that the valve seat and other parts of the SVs were damaged, and the valve was maintained in an open condition. In general, the maximum operating temperature of the SRV is 302 °C, and the maximum operating temperature of the other valves are 550 °C. Because zircaloy reacts with steam above a temperature of 900°C, it is likely that steam at a temperature considerably higher than the maximum operating temperature passed through the SVs and SRVs.

Table 4: Estimation of operating pressures for safety valves and safety relief valves

Type of Valve	Name in Fig. 16(c)	Operating Pressure (MPa)
Safety Valve (SV)	203-4A, 203-4C	8.51
Safety Valve (SV)	203-4B	8.62
Safety Relief Valve (SRV)	203-3B, 203-3C	7.64
Safety Relief Valve (SRV)	203-3A, 203-3D	7.71

Based on the accident scenario of this report, and considering Figs. 13 and 14 and the aforementioned discussion, and making a bold prediction, the destruction scenario for Unit 1 is estimated to be as follows.

1. At approximately 20:26 on March 11, high-temperature steam from the RPV passed through the SV and circulated into the D/W.As the valve seat of SV203-4C was stuck, the steam blew out through a rupture with an equivalent diameter of 1.7 cm.
2. The leaked contaminated gas from the RPV was stored in the PCV, resulting in an increase in the radiation in the R/B at that time. Accordingly, entry to the R/B was prohibited at 21:51.
3. The PCV pressure increased owing to this steam discharge, and at approximately 03:30 on March 12 a crack with an equivalent diameter of 3.5 cm occurred in the bellows of the vacuum break valve connecting the D/W and S/C in the lower part of the PCV.
4. The radiation level at the main gate increased after 04:00 due to the contaminated gas that released from the PCV to the environment.
5. The temperature and pressure of the RPV increased rapidly due to the IC shutdown at approximately 03:00; moreover, the valve seat of the SV (SV203-4A) was stuck at 06:20, resulting in a rupture with 7 cm diameter.
6. At approximately at 06:23, the crack at the bottom of the PCV widened or a new crack appeared. The size of the crack was equivalent to 8 cm in diameter. There is a possibility that the PCV was damaged again in addition to the crack at the bellows of the vacuum break valve.
7. The water in the RPV was running out, and the R/B experienced a hydrogen gas explosion at 15:36, resulting in the cessation of water injection. Moreover, at approximately at 16:00, a hole was created at the bottom of the RPV and the molten fuel was discharged. However, a significant fraction of the fuel is considered to have remained in the RPV.

For the estimation of the location of the destruction, it is essential to obtain a more detailed structure of the reactor and accurate information such as the location of the temperature sensors and the location of the SVs and SRVs. However, this information was not available at the time of writing this report. If this information can be obtained in the future, it will be possible to estimate the damage location with a higher degree of accuracy. The estimated failure location may change when the detailed reactor structure becomes known.

To contribute to the internal investigation of the PCV and RPV to be conducted in the future, the status inside the RPV can be estimated based on the accident scenario in this report. However, this is only a bold estimation; moreover, it is quite possible that the current accident scenario will be completely different when new information becomes available.

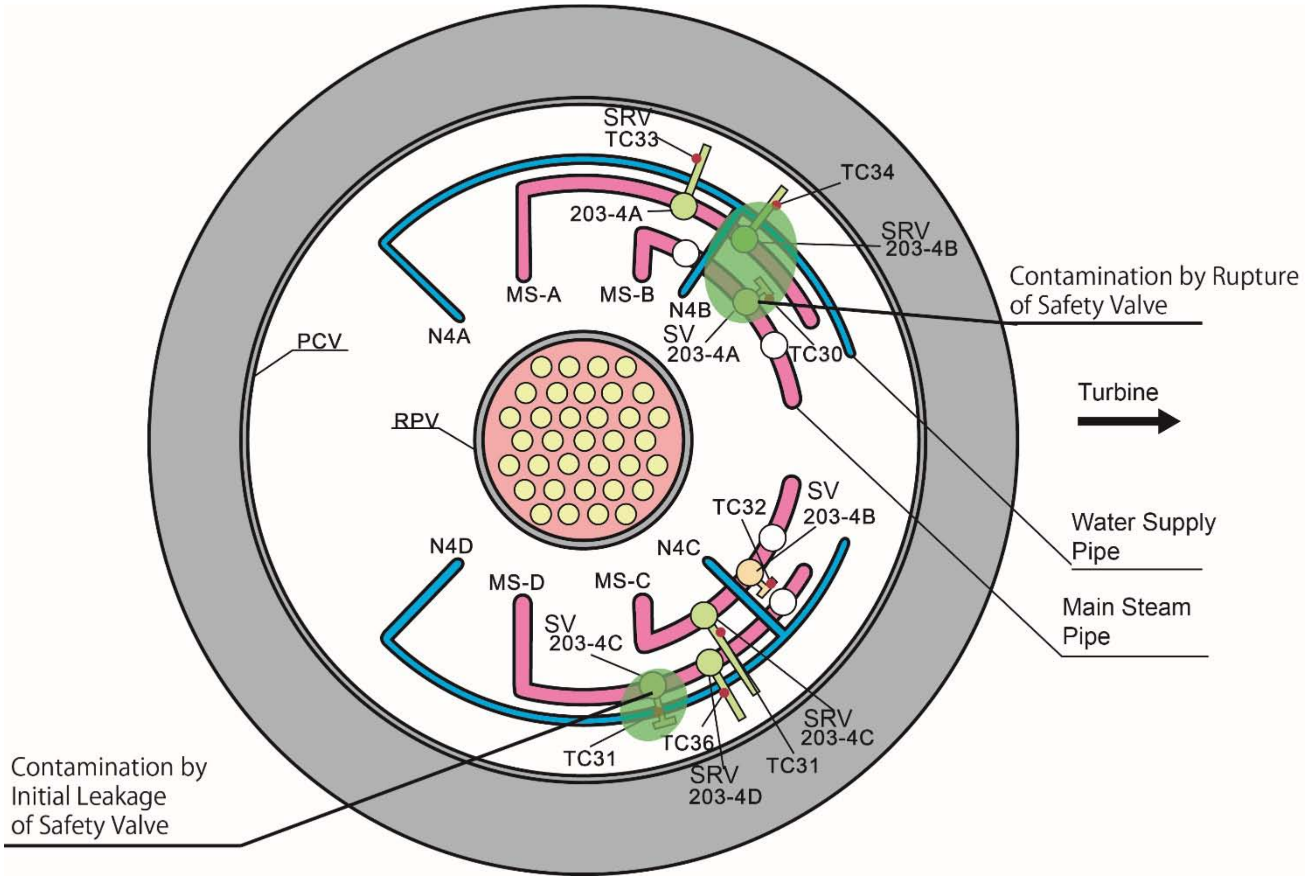


Fig. 18: Estimation of high radiation points in the PCV

Figure 18 shows the location where the radiation intensity is estimated to be high owing to this accident scenario. We estimate that the largest leak occurred at the safety valve, SV203-4A (TC30) at around 06:20. The leaked steam might have been ejected to TC34. Because the SRV valve seat is also considered to be damaged to a certain extent, the radiation intensity of the piping near the SRV (RV203-3B) is considered to be high. The next area that was considered to be contaminated is near the release port of SV203-4C (TC31). This leakage is estimated to have occurred at 20:26 on March 11.Asthe area of this leak was smaller than that of SV203-4A, the degree of contamination is not significantly large. A hole was formed at the bottom of the RPV at approximately 16:00 on March 12, and the injected water probably leaked out from there.

If the estimation in this report is accurate, the water level in the RPV decreased below the TAF, and hot water vapor and hydrogen gas were generated; the leaked high-temperature gas resulted in sticking of the seat of the SV. The BWR is not designed for the water level to decrease below the TAF; however, the risk of the reactor water level falling below the TAF and the resulting hot gas destroying the SV must be considered, as in the Fukushima Daiichi NPP accident. If the materials of the valve seat and spring of the SVs are manufactured to withstand high temperatures, operational difficulties such as the gas tightness of the valve are also expected to arise. However, to ensure the safety of the reactor, certain operational difficulties may be acceptable.

At the Fukushima Daiichi NPP, two emergency diesel generators were installed on the same floor for operational simplicity. Neither of these emergency systems functioned when the tsunami entered the R/B. Although operational difficulties are expected to arise, to prevent future accidents at NPPs, it is considered necessary to improve safety when the reactor water level decreases below the TAF.

VIII. Conclusions

To prevent future nuclear accidents, the accident at Fukushima Daiichi NPP must be properly analyzed and understood. We had been analyzing the accident since its occurrence [2]. According to the original records and witnesses, we verified that the IC of Unit 1 of the Fukushima Daiichi NPP may have been working normally to a certain extent. Based on this assumption, we performed an accident analysis based on the accident scenario. Moreover, the behavior of the reactor water level meter at the time of the accident was analyzed, and this study attempted to reproduce the measurement data of the reactor water level meter during the accident. To contribute to the investigation of

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nuclear accidents in the future, we attempted to estimate the failure locations and failure times of the RPV and PCV without fear of being accused of inaccuracy.

The predictions of the accident analysis have many possibilities under the different accident scenarios; moreover, the present predictions may not be accurate. However, there was only one true event of the accident that really happened.

The results obtained from the analysis are as follows:

1. The original data reported in the first stage of the accident and the evidence obtained from the operators were examined to clarify the behavior of the ICs. There are records that the water injection to the reservoir tank of IC-A was executed. There was a possibility that MOVs were open during the tsunami attack, and that IC-A was working after the tsunami attack until approximately 03:00 on March 12, 2011.
2. The present accident scenario estimated that the initial RPV leak occurred at 20:26 on March 11 and the pressure in the PCV increased because the steam and gas from the RPV were directly blown into the D/W. This scenario agrees with the increase in radiation intensity that was recorded in the R/B at 21:51. Owing to the increase in the PCV pressure, the PCV ruptured at approximately 03:30 and 06:23 on March 12 at the bellows of the vacuum breaker tube connecting the D/W and S/C. This estimation agrees with the radiation dosage and pressure data obtained during the accident.
3. It is estimated that the RPV ruptured at 06:20 on March 12 in the vapor phase of the vessel after the IC stopped functioning. The RPV ruptured again at approximately16:00 at the bottom of the vessel, because the water dried out. Molten fuel may have spilled out to the PCV; however, the amount of fuel that melted was not as large as reported by TEPCO. This estimation agrees with the temperature data measured immediately after the accident and the radiation-dose data measured in the NPP.
4. The author attempted to present bold predictions of the positions and times of vessel ruptures according to the present scenario at the accident site and the temperature data in the reactor, which were obtained after March 20. The temperatures of Unit 1 increased up to 400°C on March 22, and they gradually decreased with the increase in injection water. We examined the details of the temperature data that high temperatures were recorded at several locations after water injection. Thus, we concluded that the leakages from the RPV at 20:26 on March 11 and 06:20 on March 12 occurred at the SVs, because the significantly high-temperature steam that passed through the valve destroyed the valve seat. Some of the SRVs may have suffered the same process.

IX. Epilogue

It is difficult to predict the phenomena of a serious accident in real time. At the beginning of an accident, only limited data is available, and even that data is often inaccurate. The accident scenarios that are estimated from these data may be different from the truth.

During the Apollo 13 accident in 1970, the teamwork between the astronauts and the ground group resulted in the miraculous survival of the astronauts. The subsequent investigation, at least as far as the author knows, was conducted quickly and fairly, and not long after, the subsequent set of astronauts landed on the moon.

The star probe Hayabusa, which landed on the asteroid Itokawa in 2005, failed at its first landing. Based on the analysis results from that time, the landing was retried. The team on Earth estimated the conditions of Hayabusa based on the intermittent and insufficient information sent from Hayabusa and took appropriate action.

At the time of the accident at the Fukushima Daiichi NPP in 2011, Units 1-4 of the plant were only less than a kilometer away from the seismically isolated critical building where the headquarters of the task force were located; however, adequate data were not obtained. The case where the operators could not reach to the object was similar to that of Hayabusa, which stayed on the asteroid Itokawa, 300 million kilometers away from the Earth.

When faced with a serious accident, it is important to respond to the incident with flexible thinking according to the situation, similar to the actions of the Hayabusa and Apollo 13 teams. In the case of the accident at the NPP, I wonder if the concerned personnel were able to analyze and respond appropriately to the situation with a clear and flexible mind.

During the Fukushima Daiichi NPP accident, it was initially impossible to get an accurate understanding of the reactor status. Even the wrong data at the time of the accident can be corrected based on reasonable explanations to derive accident scenarios that are closer to the truth. Furthermore, by considering the new data obtained from the internal investigation of the reactor, it is possible to clarify the scenario of the accident more accurately.

Ten years after the accident, it is now possible, to a certain extent, to present scenarios that are closer to the truth of the accident. However, from the perspective of exploring events from the still limited data, elucidating the accidents at NPPs is somehow similar to archeology, where we look at dinosaur fossils and attempt to deduce the life trends of dinosaurs that lived 150 million years ago.

It is our duty as scientists and engineers to clarify the real phenomena of the nuclear accident, and to present suggestions for the prevention of nuclear accidents that will occur in the future. We must not distort the historical facts of the nuclear accident for the sake of the reputation of the academician, appearances of the academic community, or the interests of the organization. Several academic societies and organizations have published many reports on nuclear accidents. I wonder if these reports are the result of sincere discussions among scientists and engineers on all possibilities and an attempt to deduce the truth.

In the current situation where we do not know the condition inside the reactor, there are numerous possibilities for nuclear accident scenarios. The accident scenarios in this report can explain the data and events at the time of the accident relatively well. However, I do not believe that all estimates and accident scenarios are accurate. There is only one true event that actually occurred during the nuclear accident. In the future, it is necessary for scientists and engineers to get closer to the truth by conducting serious discussions with each other.

It is important to understand the actual events that occurred at the Fukushima Daiichi NPP. An accurate understanding of the phenomena should contribute to the early termination of the nuclear accident, and prevent similar accidents from occurring in NPPs around the world. Japan, which has suffered a significant amount of human, financial, and cultural damage, should take the leadership in providing the world with accurate accident analysis and guidelines for preventing its recurrence.

Acknowledgments

I would like to express my gratitude to colleagues and professors of academic societies who provided me with various information that aided in producing this report. The faculty members and students of my laboratory helped to arrange and analyze the data. In particular, I would like to thank the students who stayed in Sendai during the accident and helped us as a contribution to society, instead of going to volunteer for disaster recovery. I would also like to express my gratitude to Mr. Shuichi Moriya, a technical staff member of my laboratory, for his assistance in preparing the figures.

Abbreviations

AOV	air-operated valve
BAF	bottom of active fuel
BWR	boiling water reactor
D/W	drywell
HTC	Rep. #, date: Maruyama S., Komiya A., and Okajima J., Heat Transfer Control Laboratory, Institute of Fluid Science, Tohoku University, Report, 2011-2015 http://www.ifs.tohoku.ac.jp/komiya/maru/atom/index.html
HPCI	high pressure coolant injection system
IAEA	International Atomic Energy Agency
IC	isolation condenser
MAAP	Modular Accident Analysis Program
MOV	motor-operated valve
NPP	nuclear power plant
NRA	Nuclear Regulation Authority of Japan
PCV	primary containment vessel
PLR	primary loop recirculation system
R/B	reactor building
RCIC	reactor core isolation cooling system
RHR	residual heat removal system
RPV	reactor pressure vessel
S/C	suppression chamber (suppression pool)
SRV	main steam safety relief valve
STGS	standing gas treatment system
SV	safety valve
TAF	top of active fuel
TC	thermocouple
TEPCO	Tokyo Electric Power Company

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A Crowd Monitoring Methodology based on the Analysis of the Electromagnetic Spectrum

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Abstract- In this work, a system able to monitor the crowd density detecting mobile phone communications through the analysis of the electromagnetic spectrum is proposed and experimentally assessed. The variations of the electromagnetic spectrum are collected with a low-cost spectrum analyzer, and a high gain log-periodic directive antenna (LPDA). The objective is to relate the spectral power density in a given frequency band to estimate the connections present and the number of people in a given area. In particular, a linear regression estimator, whose parameters have been calculated with the least square method modeled considering experimental data in a controlled environment, permits us to infer the number of customers detected on a given frequency band. The obtained experimental results demonstrated the efficacy of the method, which can be used not only to monitoring the number of people in a given scenario, but it also be used for commercial activities to detect the presence and pervasiveness of different mobile phone companies.

Keywords: *statistical analysis; electromagnetic spectrum analysis; spectrum analyzer.*

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Massimo Donelli [α] & Giuseppe Espa [σ]

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I. Introduction

In the last decade, there has been a growing interest in security applications and, in particular of techniques to crowd density estimations in critical areas such as airports, stadiums, supermarkets, and other aggregation areas (Singh et al., 2020; Rahman et al., 2006; Ohmann et al., 2006; Oeimiane et al., 2020; Jeong et al., 2013). The most popular techniques aimed at detect crowds are based on image processing (Paulsen et al., 1997; Velastin, 1994; Marana, 1997; Jarndal & Alnajjar, 2018), but they require video cameras, and infrastructures to correctly work (Paulsen et al., 1997). Other systems make use of acoustic sensors distributed in a given area like in (Zappatore et al., 2017). Other techniques make use of a radiofrequency identifier (RFID) tag (Weaver et al., 2013) or wearable dedicated electromagnetic sensors (Paine, 2008; Kulshrestha et al., 2020) that people must wear, so they are not suitable in a situation where individuals are not collaborative. Recently the great diffusion of mobile phones makes possible the development of methods to monitoring the crowd by using the signals emitted by phones (Heath et al., 1998; Hudec et al., 2005; Puscasiu et al., 2016), unfortunately, the mobile phone companies do not provide the information related to protecting the user's privacy, and a direct localization of the users is impossible (Aziz & Bestak, 2018; Pinelli et al., 2015). Moreover, each mobile company is assigned a limited portion of the electromagnetic spectrum, and to increase the user and maximize the channel number, the companies make use of time and frequency domain multiplexing methods that make the localization and estimation of user number quite complex. In this work, a compact, light, and portable system, that does not require specific infrastructures such as cables, mechanical supports, or dedicated computational resources is proposed. This system is based on the analysis of the electromagnetic spectrum by using a spectrum analyzer (SA) (Bertocco et al., 2006) to calculate the power spectrum density on the whole mobile phone channels used by mobile phone companies. In particular, despite the limited number of mobile radio channels, when lots of users have connected, the power spectrum density increase. The goal is to found a relation between the user's number and the power spectrum density deriving a specific model based, in particular, the simple linear regression model (Kutner, 2005; Afifi et al, 1967; Mahmud et al., 2010), is considered, and its parameters are derived by mean of a set of measurements in controlled environments. The proposed system not only permits to estimate of the crowd density in a given area but also makes it possible to evaluate the number of users for each mobile company providing their diffusion in a given urban area, and from a marketing point of view, this is a great advantage. The manuscript is organized as follows: Section II introduces the description of different mobile phone standards and the mathematical formulation for the regression model. Section III reports the system calibration and a selected set of experimental results related to real scenarios. Finally, Section IV concludes.

II. Mathematical Formulation

In the following, a brief description of how the electromagnetic spectrum is used by the different mobile standards is reported. In particular, in mobile networks, and Absolute Radio-Frequency Channel number - ARFCN is used to identify a pair of physical radio carriers that are used for transmission and reception in a mobile radio system; one carrier is

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associated with the uplink channel, the other to the downlink one. In GSM (2G technology), uplink and downlink channels are identified by ARFCN. With the time-based component Time-Division Multiple Access – TDMA (Robert & Barra, 2001), physical channel in GSM is defined by a specific ARFCN and a relative time slot. The proposed system does not consider 2G technology because it is obsolete and almost completely non-used. The system considers 3G and 4G technologies because they are the most diffused and used nowadays. In UMTS for third and fourth generations, ARFCN has been replaced with UARFCN and EARFCN, which are simpler and always have a direct relationship between the frequency and the associated channel number. A UARFCN - UTRA ARFCN, where UTRA stands for UMTS Terrestrial Radio Access, is used to identify a pair of frequency channels as in 2G but in the UMTS frequency bands, the same for EARFCN. Tab I shown the channels dedicated to the different standards, while Table II details the channel number and the bandwidth associated with each mobile company. Every channel has a bandwidth of about 5 MHz. To measure the channel's power devoted to mobile communication, a digital spectrum analyzer (DSA) and a broadband log periodic antenna (LPDA) were used. In particular, the DSA integrates the fast Fourier transformer (FFT) samples in the whole frequency spectrum measured by DAS considering the following relation:

$$P_{ch_n} = \frac{\sum_{m=0}^{M} 10^{\frac{FFT\left(f_{start\ ch_n}+m\Delta f\right)}{10}}}{WB} \tag{1}$$

where WB is the window bandwidth, and it is equivalent to the noise bandwidth of the resolution bandpass filter of the DSA, $ch_n = \{n = 1, 2, 8, 7, 20, 32, 38\}$ is the band number related to the different standard, Δf is the resolution of the SDA video filter, *FFT*(*f*) is the spectral power measured at frequency *f* and it is expressed in dBm and M is the number of samples of the FFT. When connections will increase also the channel's power increases; consequently, it is worth noticing that the channels number is limited, and they are used using time and frequency multiplexing techniques to increase the user's number. The measure of total spectrum power $TPS = \{\sum_{n=\{1,3,7,8,20,32,38\}} P_{ch_n}\}$ can provide an estimation of customers connected x. In particular, the goal is to find a model able to describe the relationship between the total power spectrum versus the user's number $TPS\{\xi\}$. The model can be described with the dependent variable $TPS\{\xi\}$ and the independent variable ξ, since we are dealing with two quantitative variables, it is possible to consider a simple linear regression model (Kutner, 2005; Afifi et al., 2005, Mahmoud et al., 2004) expressed by the following relation:

$$TPS(\xi) = \alpha_0 + \alpha_1\xi + \varepsilon \tag{2}$$

where α_0 and α_1 are the predicted value of the total power spectrum when $\alpha_0 = 0$ and the regression coefficient, respectively. The two coefficients α_0 and α_1 can be easily estimated by using the ordinary least square (OLS) as follows:

$$\alpha_0 = \frac{\sum_{h=1}^{H} TPS_h \sum_{h=1}^{H} \xi_n^2 - \sum_{h=1}^{H} \xi_n \sum_{h=1}^{H} \xi_h TPS_h}{H \sum_{h=1}^{H} \xi_n^2 - \left(\sum_{h=1}^{H} \xi_h\right)^2} \tag{3}$$

$$\alpha_1 = \frac{H \sum_{h=1}^{H} \xi_n TPS_h - \sum_{h=1}^{H} \xi_n \sum_{h=1}^{H} TPS_h}{H \sum_{h=1}^{H} \xi_n^2 - \left(\sum_{h=1}^{H} \xi_h\right)^2} \tag{4}$$

Where H is the total number of measured samples, thanks to relations (2), (3), and (4), it is now possible to relate the number of users versus the total power spectrum measured with the spectrum analyzer.

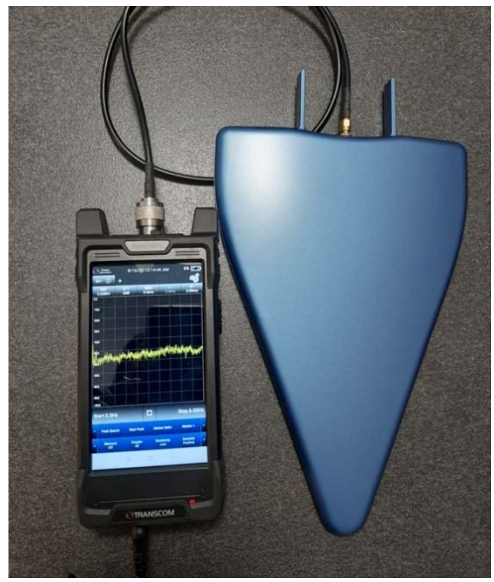


Fig. 1: Spectrum Analyzer and broadband Antenna used for the measurement campaign

Table 1: Channels and frequancies for the different communication standard

Freq. [MHz]	Band Number	Standard
800	20	4G
900	8	2G/3G
1500	32	4G
1800	3	2G/4G
2100	1	3G/4G
2600	7/38	4G

III. Calibration and Experimental Assessment of the System

In this section, the calibration and experimental assessment of the proposed system are carried out. First of all, a set of measurements has been done to estimate the coefficients of the linear regression model. Then a measurement campaign is carried out in a realistic scenario.

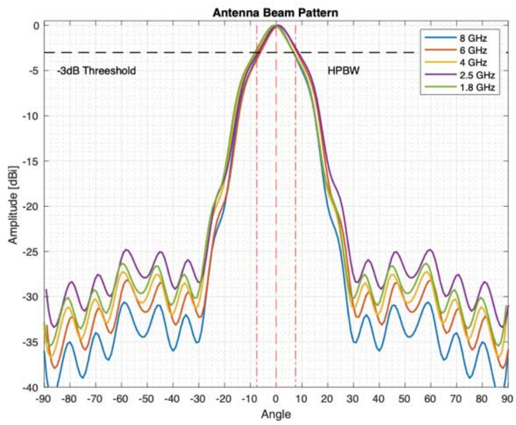


Fig. 2: Log periodic directive antenna (LPDA) beam pattern.

a) System Description

The system is composed of a handheld digital spectrum analyzer SpecMini (Transcom Instruments Company), with a frequency range 9KHz-6.0GHz, sensitivity -168dBm, and a resolution bandwidth from 10Hz up to 5MHz. A broadband directional log periodic antenna SPM-AS100 with a frequency band from 700MHz - 6GHz, a gain G=5 dBi and an antenna factor of 26-41 dBi. The antenna is quite directive, with a main beam aperture angle of about 7 degrees. The SA is equipped with an android operative system and a WIFI card to record and transmit the data. A photo of the device is reported in Fig. 1, while Fig. 2 reports the antenna beam patterns for different frequencies. The beam pattern reported in Fig. 2 demonstrates the good directivities capabilities of the considered LPDA. Thanks to the short angular aperture of the LPDA main beam, it is possible to steer it by using a suitable mechanical pedestal to properly delimit a given area; at the same time it permits to limit or to completely remove (especially in the backside direction) the interfering signals produced by unwanted repeaters or radiofrequency generators. It is worth noticing that the spectrum analyzer can correctly identify the channels of each specific mobile phone companies assuring the mitigation of interfering effects produced by unwanted electromagnetic sources. As it can be noticed the proposed system is compact, light, and easily transportable, it does not require specific infrastructures such as cables, mechanical supports, or dedicated computational resources. To be operative you have only to place the SA and steer the main beam of the LPDA, along the area under investigation.

b) Calibration

To derive the coefficients mandatory to implement the linear regression model, a set of measurements considering several users have been carried on, in particular, a different number of users have been activated and the power spectrum measured by using the handheld digital spectrum analyzer specmini and the LPDA antenna. In particular, the experiments considered up to 100 users with mobile phones of different companies.

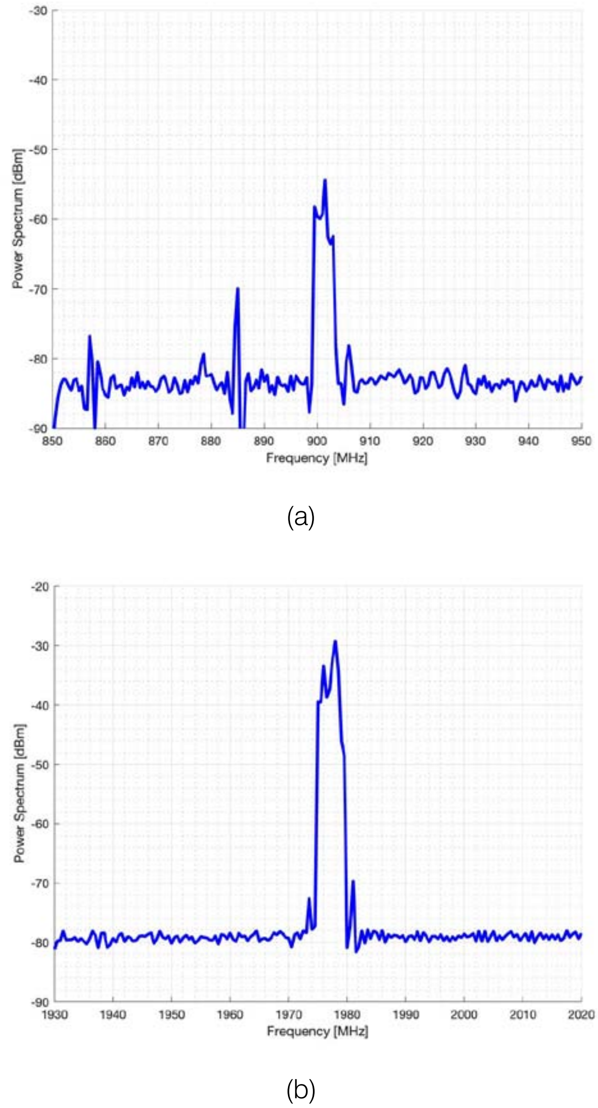


Fig. 3: Measured signal spectrum, single connection (a) 3G standard UARFCN=3038 - UL=902.6 MHz (b) 3G standard UARFCN=10838 UL=1977.6 MHz.

In the following, a selected set of the measured spectrum has been reported for different standards and user numbers. The measured spectrum for one and two users connected with 3G and 4G standards are reported in the following. Figs. 2 (a) and (b) represent the measured spectrum used to download or loading some contents such as video or music; in particular in Fig. 2 (a) can be observed a peak at 902.6 MHz, which is presented by the service provider as an uplink channel, while in 2 (b) the frequency peak is located at 1977.6 MHz, also in this case declared by the service provider as the uplink channel.

The data reported in Figs. 2 (a) and (b) indicated that the bandwidth is 5 MHz as expected.

For the sake of comparisons, Figs. 3 (a) and (b) report the measured spectrum when two users using 4G standards are downloading or sharing content on the wireless channel. In

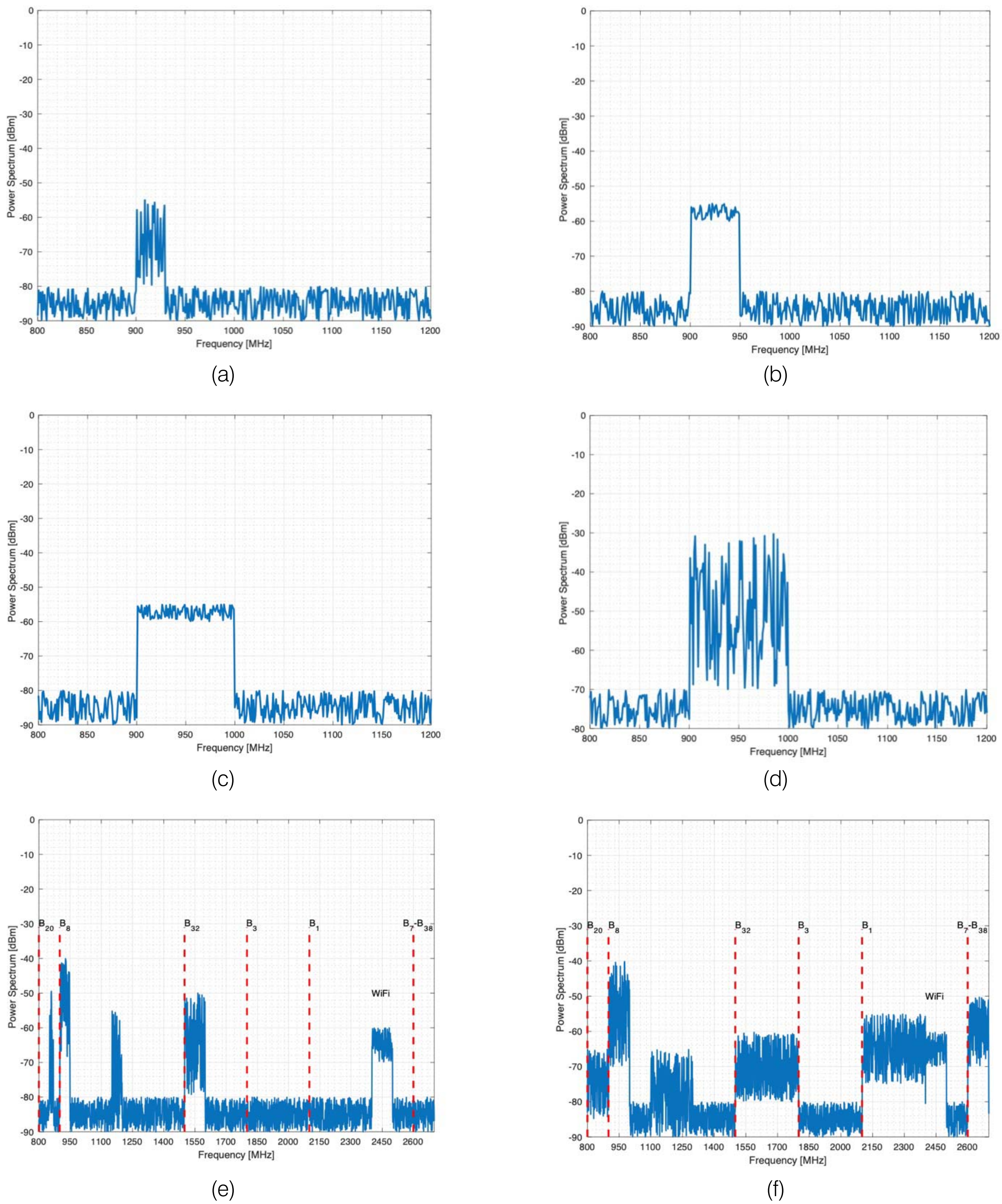
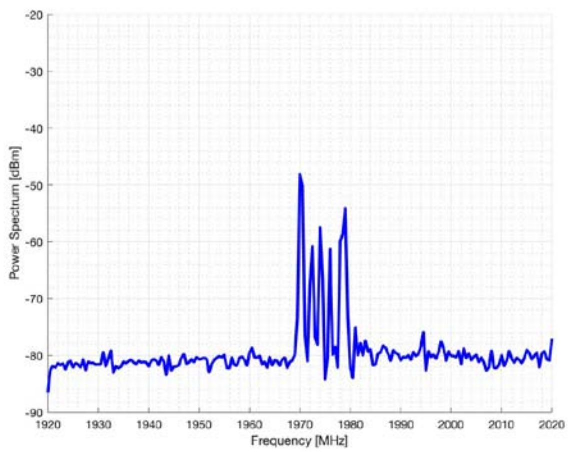


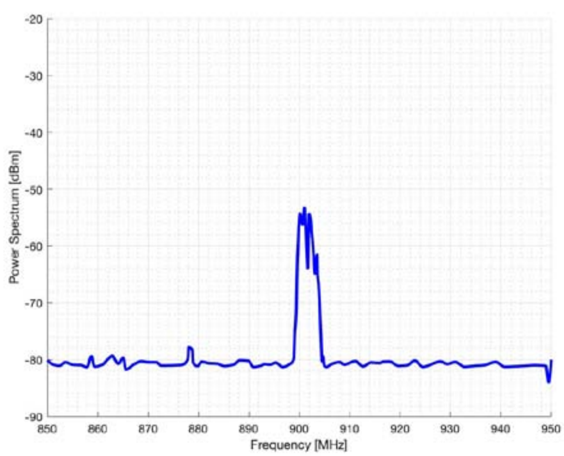
Fig. 4: Measured signal spectrum versus users number: 3 users (a), 5 users (b), 10 users (c), 15 users (d), 30 users (e), and 100 users (f).

Table 2: Number of Channels associated to the four main mobile communication Italian companies. Each channel has 10MHz bandwidth. Frequency Division Duplex (FDD) and Time Division Duplex (TDM) are considered to increase the number of users

Band	TIM	Vodafone	Wind/HG3	Iliad
b1(2100 MHZ)	30	30	40	20
b3(1800 MHz)	40	40	40	20
b8 (900 MHz)	20	20	20	10
b7-b38(2600MHZ)	30	30	70	20
b20 (800 MHz)	20	20	20	-
b32 (1500 MHz)	20	20	-	-



(a)



(b)

Fig. 5: Measured signal spectrum, double connection (a) 4G standard EARFCN=501 - UL=1970.1 MHz (b) 4G standard EARFCN=1850 UL=1775.0 MHz

Fig. 3 (a) shows a connection at 1970.1 MHz declared by the service provider as an uplink channel. The measured bandwidth is about 10 MHz. Fig. 3 (b) reports the measured spectrum when two users with 4G standards are connected. The channels are centered at 902.6MHz (uplink channel), and the bandwidth is higher concerning the previous measures related to single users reported in Figs. 2 (a) and (b).For the sake of completeness, the measurements obtained with 3, 5, 10, 15, 30, and 100 users are reported in Figs. 5 (a), (b), (c), (d), (e) and (f) respectively. As it can be noticed from the electromagnetic spectrum measurements reported in Figs. 5 when the number of users increases and the channels are filled to guarantee the connectivity of users, the Time-Division Multiple Access – TDMA (Robert & Barra, 2001) is activated, at each user is associated given time-slots and consequently the signal variation increase as well as the power spectrum intensity. This is quite evident in Figs. (c),(d) and (e),(f) respectively. At the end of measurement, the mandatory information for the estimation of correlation coefficients is available. In particular, the obtained correlation coefficients are reported in Fig. 6 and used in the linear regression model expressed by relation(2).

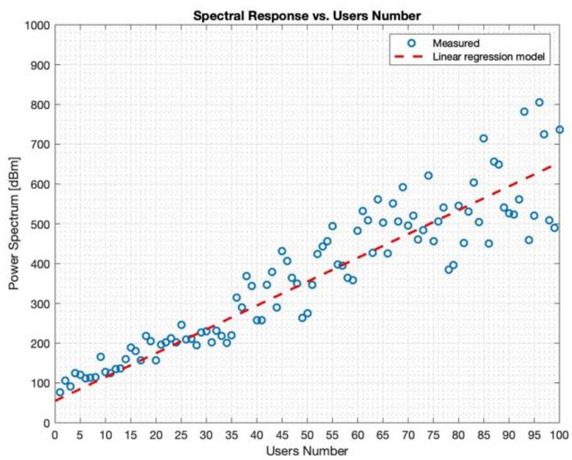


Fig. 6: Linear regression model coefficients are estimated using the measurement campaign

c) Experimental Assessment

In this section, the proposed system has been experimentally assessed in realistic environments. In particular, the measurement campaign has been done in the University library and canteen/bar. The first scenario concerns the University library, the SA and the antenna are placed in the outdoor courtyard of the university library, the main beam of the LPDA antenna was steer to cover the whole library building and avoid interfering signals coming from other users in particular, in the back direction of the main antenna beam. All mobile phones make use of a nearby base station (BS) to manage the various phases from the beginning to the end the communication. If the BS signal is strong enough to be received and interpreted by the mobile phone, this means that it is under the coverage of the base station. Usually, in urban areas, there are different base stations aimed the cover a limited amount of space called cells. The mobile phone will connect with the BS characterized with the stronger signal. The base station signals present in the scenarios under investigation are always active, and their signals are measured and taken into account, as background noise, by the spectrum analyzer. The spectrum analyzer is programmed to record the electromagnetic spectra continuously for 24 hours. The data are elaborated directly by the SA that estimates the power spectrum distribution considering all the mobile phone channels.

Then the linear regression model is considered to estimate the user's number belonging to the library. Fig. 4 reports the user number versus time estimated with the linear regression model. The data are reported in the graph every half hour for the whole measurement campaign. As it can be noticed, before the library opening, no signals are detected. Then when the library opens at 8 AM, students will arrive, the signal increase like the user number.

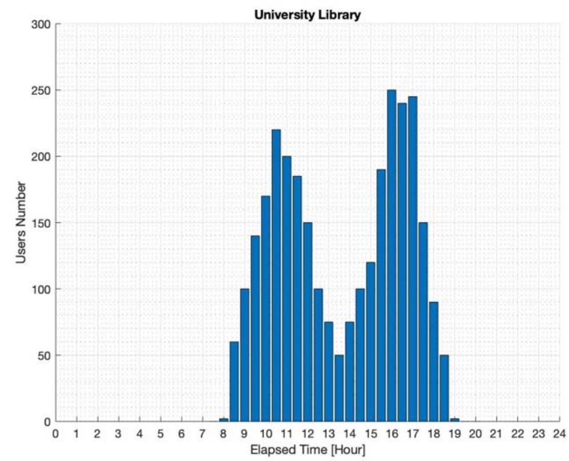


Fig. 7: University Library 24h measurement campaign. Number of users estimation vs. time

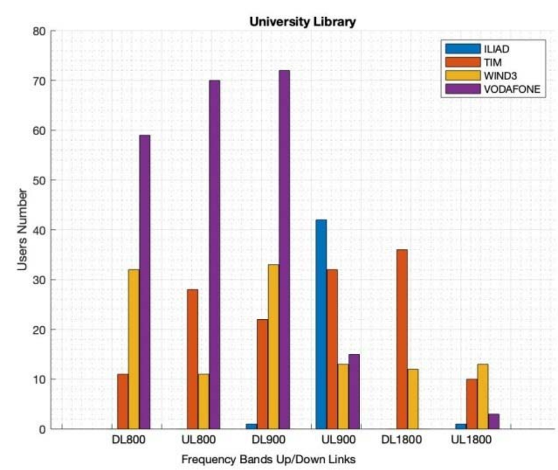


Fig. 8: University Library 24h measurement campaign. Companies distribution

Then during the lunch interval between 12 and 14, the students leave the library for the university canteen, and as it can be noticed from the data of Fig. 4, the user's number decrease. The students increase after lunch, reaching an estimated maximum value of about 250 students in the afternoon. Users number decrease up to zero after half past 18 when the university library close. To obtain the ground truth, an operator counted the incoming students, the error between estimated and measured user number was less than 10%. Fig. 5 reports the distribution of mobile phone companies derived from the electromagnetic spectrum and considering the data reported in Tab. II. As can be noticed, the most and least widespread companies are Vodafone and Iliad, respectively as expected since Iliad is a very young company up to now with a low diffusion on the market. In the next experiment, the system has been placed near the university canteen and bar. Also, in this experiment, the measurement campaign was of 24 hours. Fig. 6, similarly to Fig. 4, reports the estimated user number versus time.

The student's number increases immediately when the bar opens, for breakfast, then the user number decrease, and it reaches again a maximum value during the lunchtime.

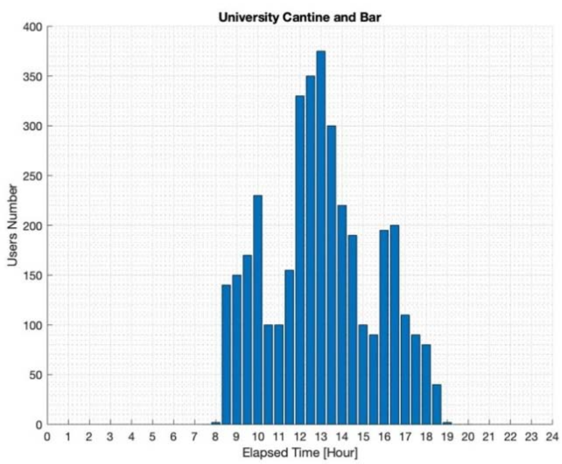


Fig. 9: University Canteen and Bar 24h measurement campaign. Number of users estimation vs. time

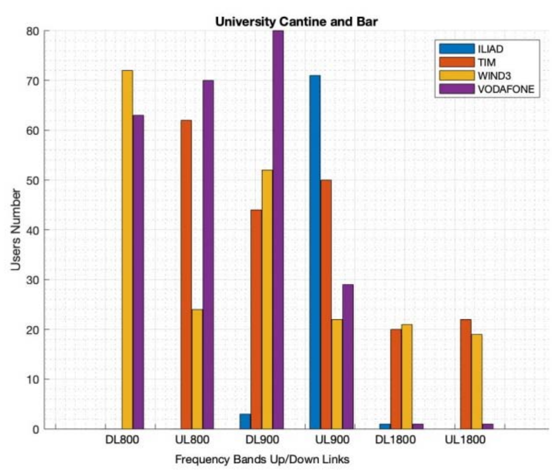
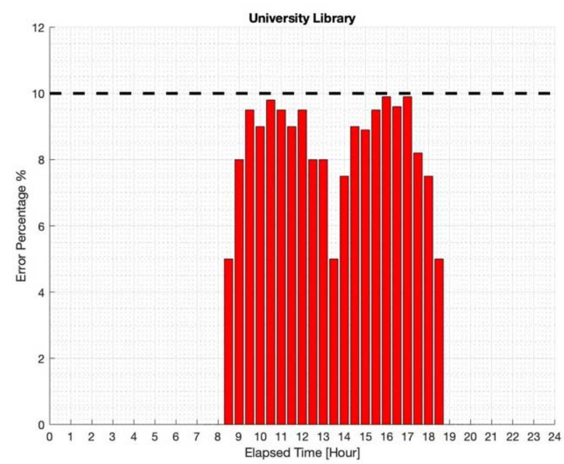
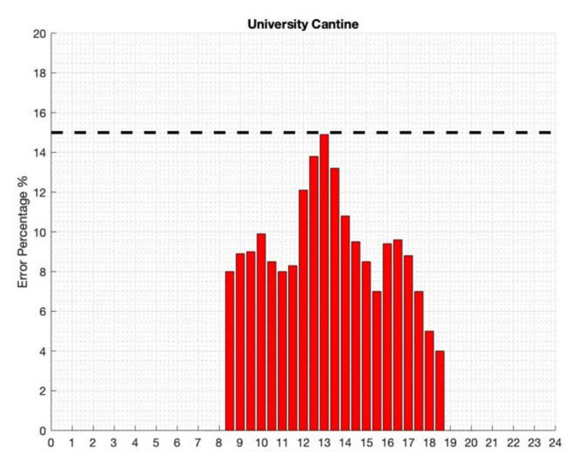


Fig. 10: University Canteen and Bar 24h measurement campaign. Companies distribution

We can observe that the maximum number of users in the canteen corresponds with the minimum number of users in the library as expected. Also, in this experiment, the company distribution has been estimated and reported in Fig. 7; in this experiment, the most widespread company was Vodafone. However, we observed a high number of TIM users as expected since it is the company adopted by the university staff. An operator counted the number of people in the canteen and bar to obtain the ground truth, the error was about 15% for all the considered scenarios. For the sake of completeness, the error versus elapsed time is reported for the two considered experimental scenarios in Figs. 11 (a) and (b), respectively. Although this method is suitable for indoor as well as realistic outdoor scenarios, some considerations concerning the presence of obstacles are mandatory. In particular, considering outdoor scenarios in rural areas, trees and leaves are the major causes of radio signal attenuation, while in urban areas, buildings, cars and buses produce attenuation and also multipath fading propagation phenomena. Due to these effects, the operative range of the systems is reduced to a limited area such as squares or small buildings like the university bar/canteen courtyard.



(a)



(b)

Fig. 11: Experimental measurement campaign, error vs. elapsed time, (a) University library, (b) university bar and cantine

Concerning indoor scenarios, the obstacles are represented by walls and furnishing. The main attenuation problems are due of bricks' walls, while furnishing, drywall, and normal concrete walls do not create big attenuation problems. The system can easily operate in rooms with shelves and furnishing such as the university library and classrooms. Of course, in well-shielded indoor locations such as cellars or garages where the electromagnetic signal of mobile phones is stopped by reinforced concrete or thick brick walls, the system is not able to properly operate.

IV. Conclusion

In this work, a system for crowd monitoring in urban areas based on electromagnetic spectrum analysis has been presented and experimentally assessed in real scenarios. The user number is monitored by analyzing the electromagnetic spectrum with a spectrum analyzer, a high gain directive log-periodic antenna (LPDA), and a suitable linear regression model. The obtained results demonstrated the effectiveness and potentialities of such a system, which can be useful to monitoring crowed areas, to assess the pervasiveness of different mobile phone companies for commercial statistics, and also to help in manage the emergency due to the COVID-19 trying to limit gatherings in public areas such as squares, airports, supermarkets, bus and train stations.

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Seeking Sustainable Development: Prospects for Saudi Arabia's Transition from Oil to Renewable Energy

By Ahmed G. Abo-khalil

Abstract- The Kingdom of Saudi Arabia (KSA) is the world's largest producer and exporter of oil with one quarter of the world's known oil reserves, i.e., more than 260 billion barrels. The KSA is also a major oil consumer, refining 2.5 million bbl/day in 2016 and consuming 3.2 million bbl/day. Of this, a substantial proportion was crude oil burned directly in power plants. Electricity demand has been rising rapidly; from 2006 to 2016, the annual average rate was 6.2%. By the end of 2016, the total electric power generation capacity of the national grid was 74.3 GW, of which 55 GW was provided by the state-owned Saudi Electricity Company and the rest by industrial companies with their own grid-connected power plants.

In 2013, to meet the needs and economic development of the future generations, the KSA announced its target to produce one third of its electricity from renewable energy by 2032 for balancing the consumption of natural resources. Fortunately, the KSA has renewable energy sources with high potential and is actively developing modern technologies for exploiting and utilizing these energy sources. The most freely available natural renewable energy sources are wind and solar energy. The KSA has an abundant potential for exploiting solar energy. The average annual solar radiation falling on the Arabian Peninsula is approximately 2200 kWh/m2. This is sufficient to make a significant contribution to the KSA's energy supply. From this viewpoint, this study reviews and explores the developments and challenges associated with renewable energy and energy efficiency programs according to the KSA's plans.

Keywords: renewable energy, energy efficiency, solar, wind, oil, sustainable.

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Strictly as per the compliance and regulations of:

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I. Introduction

Presently, energy is the most valuable tool for human communities. The present civilization would not be possible without electricity, crude oil, natural gas, and other energy sources [1]. Globally, fossil fuels are the main source of energy for the provision of electricity, heating, and transportation. Starting during the oil crisis in the 1970s, western countries began to find solutions for maintaining a source of sustainable energy that included renewables. Moreover, serious concerns about climate change and CO_2 emissions have motivated many countries to look for clean and renewable sources of energy [2]. On the contrary, the expected depletion of crude oil due to rapidly growing consumption in the Asian countries has imposed a burden on all the developed countries to find a permanent solution for sources of energy. It is common now to see wind farms, PV parks, geothermal plants, electric vehicles, and many other transformative forms of renewable energy application.

However, the world is still dependent on conventional oil (namely crude oil, condensate, and natural gas liquids). In 2008 it constituted 97% of the world's energy sources and by 2030 will remain at 90% [3]. A decline in the production and use of conventional oil is expected when the renewable sources become cheaper, more mature and their production can fill the gap in energy needs [4], [5].

World reserves of conventional oil may be depleted after several decades [6], [7]. Other researchers have expected that conventional oil would not be depleted in the next 50–60 years [8], [9] and that oil and gas depletion will not be an issue for this generation. In contrast, others contend that new discoveries of liquid fuels, and other types such as oil sands, would occur due to the rising prices and will make production sufficient to meet world demand throughout the 21st century[10], [11].

According to estimate submitted by The Kingdom of Saudi Arabia (KSA) government to Organization of the Petroleum Exporting Countries OPIC, the KSA has confirmed oil reserves of 266 billion barrels. Based on this number, the KSA's oil reserves will last for more than 70 years if the production rate is constant at 9.93 million barrels per day as reported this year. Unfortunately, the KSA is also considered as one of the top-ranking countries for CO_2 emissions and accounts for 1.4% of global emissions [12]. Therefore, emissions related to conventional oil must be reduced.

Considering these challenges, the KSA authority has launched Saudi Vision 2030, a comprehensive plan targeting the reduction in the KSA's oil dependence socially and economically. In January 2017, the KSA announced its first competitive bid for utility-scale solar power giga projects. The latest plans are described by a top-level executive in the renewable energy industry as "the highest-level commitment to renewable energy ever seen from the KSA." Additionally, the KSA has started to adopt policies for energy efficiency measures, and several initiatives have been introduced for the

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development of renewable energy projects. In 2012 the government started its ambitious plans for a $109 billion investment in renewable energy targeting the solar industry sector that would generate 30% of the KSA's electricity by 2032 [13]. The renewable energy target is shown in Fig. 1.

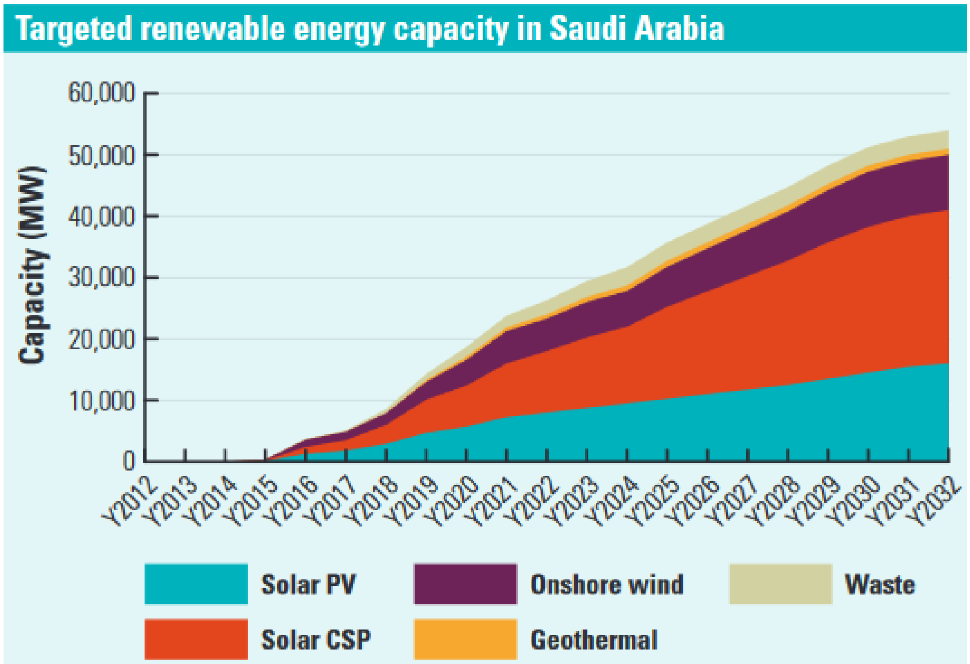

Fig. 1: Targeted renewable energy capacity in Saudi Arabia

Moreover, the KSA, a member of the Conference of Parties (COP21), submitted its Intended Nationally Determined Contribution (INDC) to the United Nations Framework Convention on Climate Change (UNFCCC). These recent plans and commitments are indications of a steadier approach from the KSA authorities regarding moving in a sustainable direction [14].

Fortunately, the KSA has various renewable energy sources such as solar, wind, and geothermal energy. The Kingdom plans to have one of the world's largest programs in renewable energy [15]. These programs have unprecedented investments and will eventually create numerous public benefits, including job creation, industrialization, energy savings, energy security, and reducing CO2 emissions. The potential benefits of adopting such targets are estimated based on the real situation in 2017 as a reference year and 2030 as a target year [16].

Moreover, the KSA has adopted a new policy for improving energy efficiency. In October 2017, the Public Investment Fund (PIF) wanted to collaborate with international partners for finding 40 GWh of energy savings in 2018. Meanwhile, National Esco, which was started with a budget of $500 million, is responsible for taking energy efficiency measures in all public buildings with 30,000 square meters or more of floor space, such as schools and mosques. All the government buildings have implemented the new energy efficiency measures to achieve the KSA's targets [17].

The KSA is increasing its dependency on renewable energy and insisting on energy efficiency measures. Several steps have been taken to transition toward a sustainable energy grid and a green economy. The aim of this paper is to demonstrate and discuss the current and future progress in the KSA's transformation to renewable energy sources especially in the solar and wind energy areas.

II. Current and Future Demand

According to the General Authority for Statistics, in 2018, the KSA's population was 33,543,987capita, whereas in 2017, it was 32,552,336 capita, i.e., a growth rate of 2.52%, as shown in Fig. 2. By 2030, the population will reach up to 39.1 million, i.e., an increase of16.7% from 2018, whereas by 2060, it is predicted to reach 47.7 million [18]. Following the population increase, electricity demand has also increased annually; the electricity use in the KSA has increased from the end of last century by approximately 8% annually. Between 2004 and 2017, there was an increase from 28 to 62.5 GW [19]. In the KSA, electricity demand has grown rapidly, for example in 2000, it was 114,161,021.00 MWh, whereas by December 2016, it increased to 287,442,172.00 MWh. By 2030, this growth in demand will require the power generation capacity to increase to 122.6 GW, as shown in Fig. 3[20].

The main consumer demand for electricity is in the residential sector. This sector is the largest with 52% of the KSA's total electricity consumption, the second largest is industrial buildings with 18%, then commercial buildings with 12%, whereas governmental buildings and agricultural activities are 11% and 3%; respectively [21]. The hot climatic conditions in the KSA results in an increased electricity consumption due to the use of air conditioners (ACs) that accounts for70% of the electricity consumption [22], as shown in Fig. 4, with summer consumption more than twice that of winter.

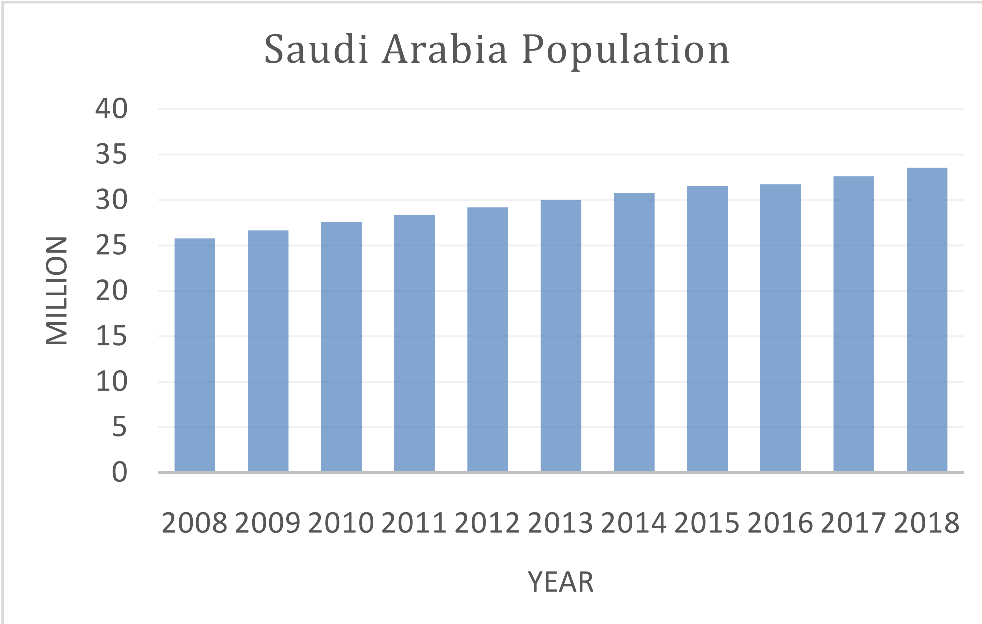

Fig. 2: KSA's population

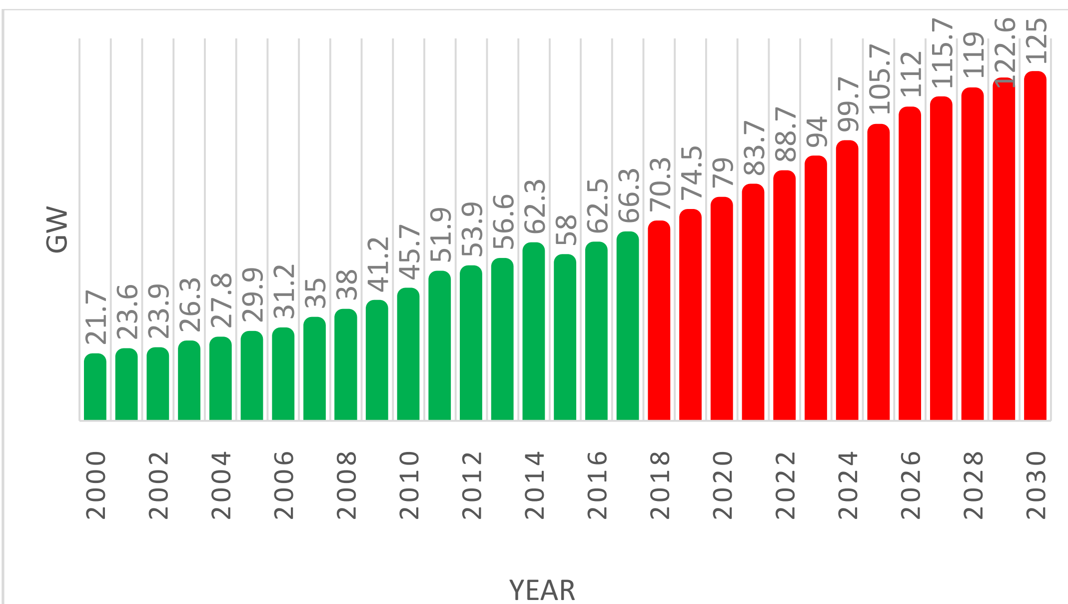

Fig. 3: Electricity demand in the KSA

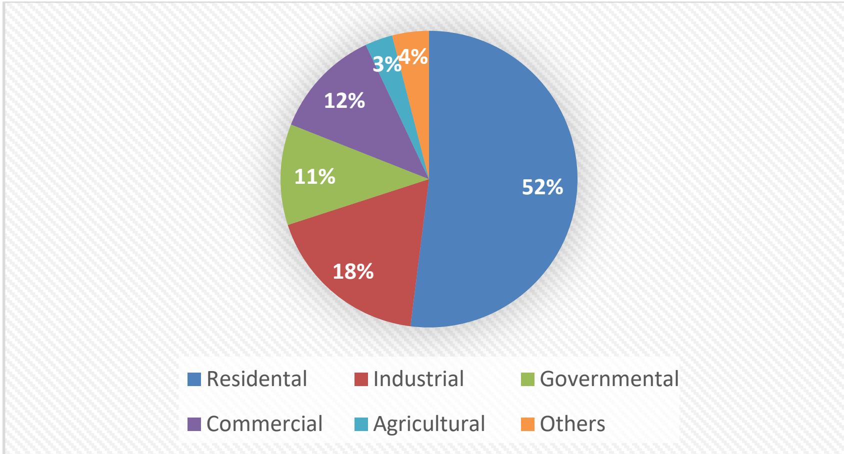

Fig. 4: Energy consumption by sector

On the contrary, the KSA has the largest water desalination plants worldwide, with 30 plants across the KSA with a capacity accounting for 18% of the total world production of desalinated water. By 2030 the KSA plans to increase the plants' capacity and add more double the water production. To achieve this capacity, an extremely high amount electricity (20%)will be required for water desalination [23].

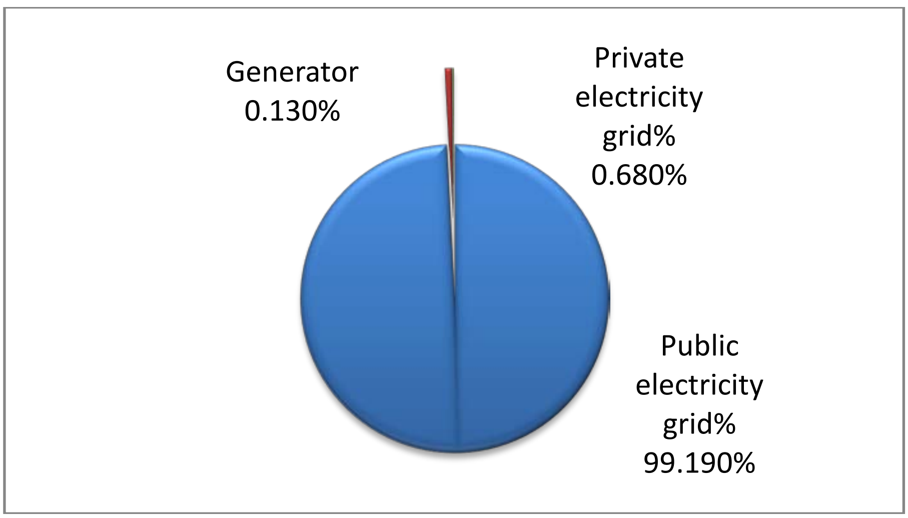

Fig. 5: Sources of Electricity Generation in KSA

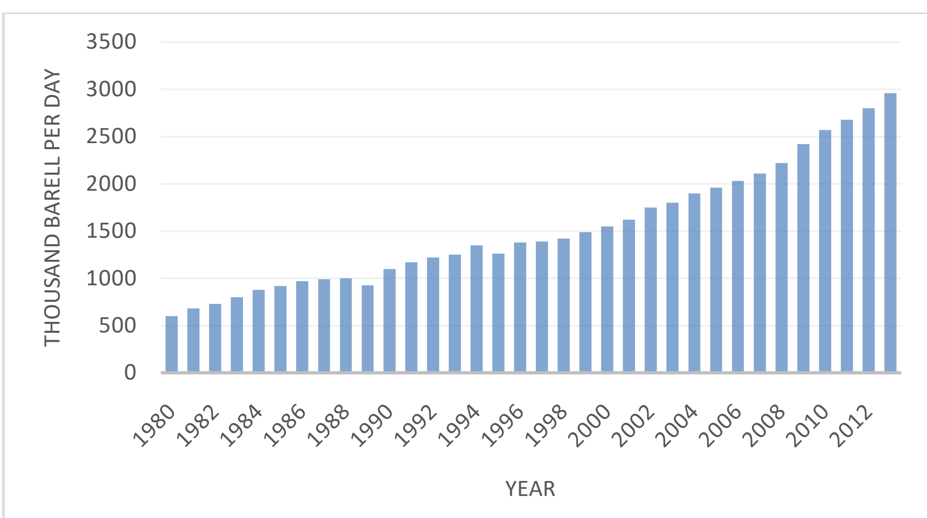

Fig. 6: Saudi Arabia Oil Consumption by Year

In a related context, the governmental data shows that 99.19% of the residential, commercial, industrial, and governmental consumers are connected to the public utility-grid, while 0.61% have their own electricity grid. In rural areas 0.13% of households have their own electricity generators as shown in Fig. 5 [24].

These statistics show that fossil fuel demand for power, industry, transportation, and desalination are estimated to grow from 3.0 million barrels of oil equivalent per day in 2013 to 8.3 million barrels of oil equivalent per day in 2028[25]. The oil consumption over two decades is shown in Fig. 6.

Taking these factors into consideration, the present path of energy and electricity consumption is not acceptable in the KSA. With these levels of consumption, crude oil is not a sustainable long-term source of energy. Saudi Aramco's CEO mentioned that increasing domestic energy consumption could cost the KSA more than 3 million barrels per day of crude oil by the end of the current decade. By 2038, the KSA could become a net oil importer without a significant reduction in oil consumption in the energy sector[26]. To avoid this and reduce the dependency on crude oil, the KSA has developed a strategy to increase the use of renewable energy, gas, and nuclear power alternatives.

Increasing energy consumption is accompanied by low energy efficiency. This is due to electricity-intensive lifestyles in buildings and transport (for AC), encouraged by the low price of electricity. The Saudi Energy Efficiency Centre was established in 2010 to develop both renewable energy and the KSA's energy efficiency policy [27].

In 2012, this developed into an interagency effort through the launch of the Saudi Energy Efficiency Program, which outlined guiding principles with strong participatory governance among key implementation agencies. These were focused on the building, transport, and industrial sectors, and covered 90% of energy consumption in the KSA, as shown in Fig. [28].

Table 1: Solar monitoring station in the KSA

Site Name	Site abbreviation	Latitude	Longitude	Elevation (m)
Afif Technical institute	Afif	23.92	42.948	1060
Al Aflaaj Technical Institute	Layla	22.28	46.73	567
Al Dawadmi college of technology	Al Dawadmi	24.55	44.47	955
Al Hanakiyah Technical Institute	Al Hanakiyah	24.856	40.54	873
Al Qunfudhah Technical Institute	Al Qunfudhah	19.11	41.08	20
Al Uyaynah Research Station	Al Uyaynah	24.9	46.39	779
Al Wajh Technical Institute	Al Wajh	26.26	36.44	21
Duba Technical Institute	Duba	27.34	35.7	45
Hafar Albatin Technical College	HafarAlbatin	28.33	45.95	383
K.A.CARE Headquarter Building	HQ Building	24.7	46.67	668
K.A.CARE City Site	K.A.CARE City	24.52	46.45	895
King Abdulaziz University (Ofsan Campus)	Ofsan	21.89	39.25	119
King Abdulaziz University (East Hada Alsham Campus)	HadaAlsham	21.8	39.73	245
King Abdulaziz University Main Campus	KAU main	21.49	39.24	75
King Abdullah University of Science and Technology	KAU ST	22.3	39.1	34
King Fahd University of Petroleum and Minerals	KFPUM	26.3	50.144	75
King Faisal University	Al Ahsa	25.35	49.59	170
Majmaah University	Majmaah	25.86	45.4	722
Qassim University	Qassim	26.35	43.77	688
Saline Water Conversion Corporation (Haql)	Haql	29.29	34.9	36
Saline Water Conversion Corporation (Umluj)	Umluj	25	37.27	10
Saline Water Research institute	Aljubail	26.9	49.76	89
Salman bin Abdulaziz University	Al kharj	24.15	47.27	465
Shaqra University	Shaqra	25.1727	45.14	804
Sharurah Technical Institute	Sharurah	17.47	47.08	760
Tabuk University	Tabuk	28.38	36.48	781
Taif University	Taif	21.43	40.49	1518
Timaa Technical Institute	Timaa	27.61	38.52	844
University of Dammam	Dammam Univ.	26.39	50.19	28
Wadi Addwasir College of Technology	Wadi Addwasir	20.4	44.89	671

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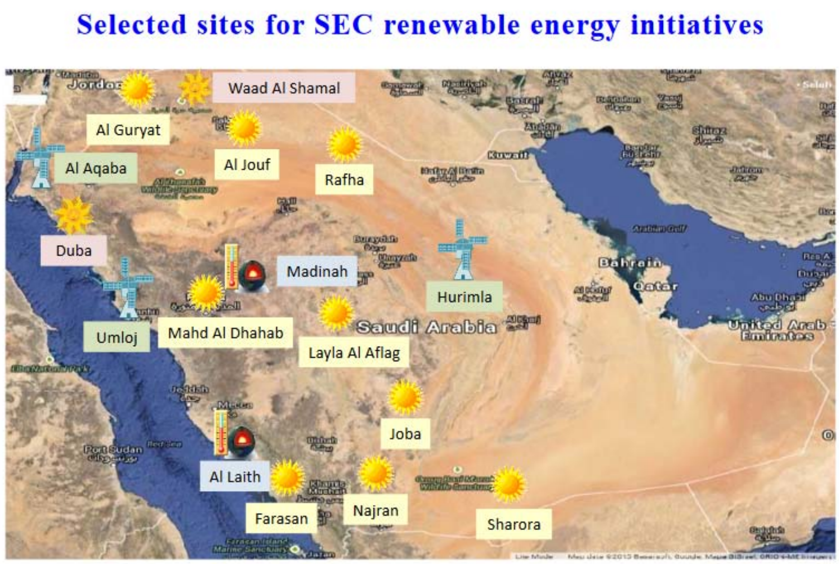


Fig. 7: Selected sites for renewable energy initiatives in the KSA

In January 2018, the electricity and water tariffs were increased, which impacted residential customers who consume more 4,000 kWh per month. The new prices boosted the economic efficiency, curbed the consumption of natural resources, and increased the share of the non-oil sector in power generation [29], [30].

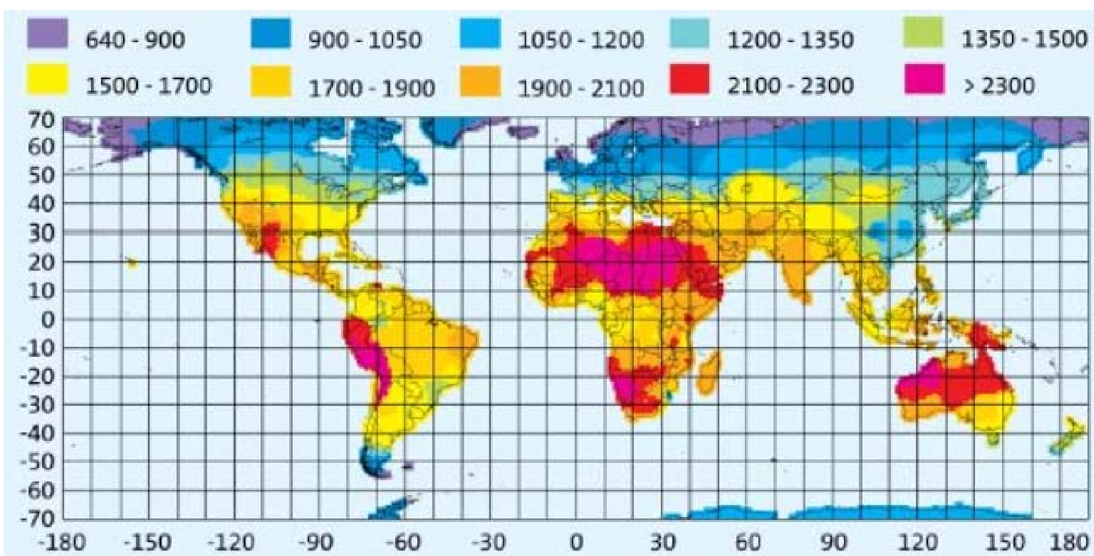


Fig. 8: Global solar atlas

Table 2: Summary of the solar irradiance components over 1 year

	Average daily total GHI WH/m^2	Average daily total DNI WH/m^2	Average daily total DHI WH/m^2	Maximum daily total GHI WH/m^2	Maximum Daily total DNI WH/m^2	Maximum daily total DHI WH/m^2
HafrAlbatin	5919	5673	2193	8599	10382	5203
KFPUM	5781	5409	2113	8474	10079	5334
Al Ahsa	6083	5480	2369	8417	9694	5520
Aljubail	5753	5464	2078	8428	9932	5117
Damam Univ.	5831	5522	2099	8416	10135	5429
Eastern Average	5874	5510	2170	8461	10049	5240
Sharurah	6735	6447	2301	8431	10498	5534
Wadi Addwasir	6559	5946	2437	8501	9168	5222
Southern	6647	6196	2387	8466	9833	5378

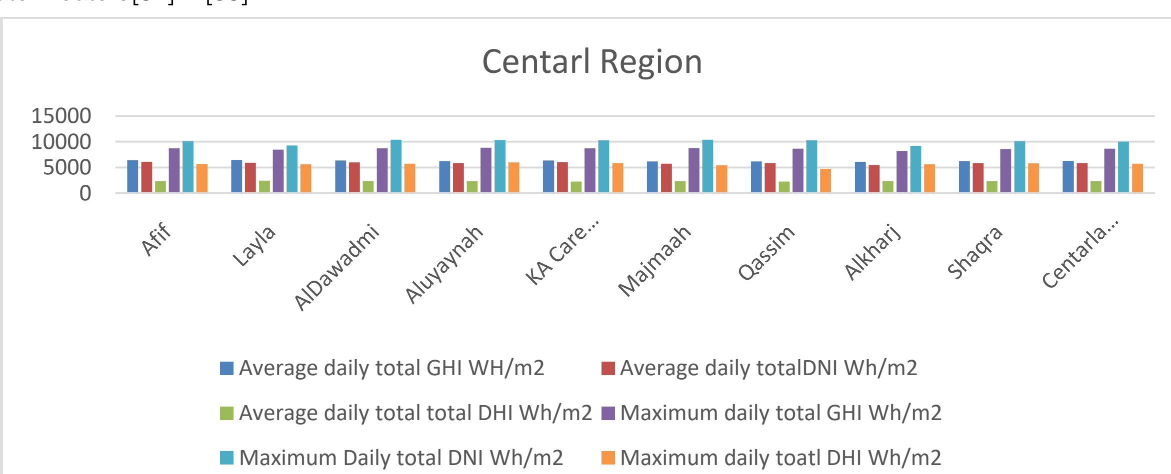
Average						
Alqunfudhah	5832	4419	2644	7720	8192	4739
Alwajh	6154	6936	1642	8367	10296	4239
Duba	6135	7170	1526	8458	10663	4513
Osfan	5957	5281	2302	8084	9481	4594
HadaAlsham	6007	5306	2297	8349	9852	4629
KAU Main	5924	5142	2329	8066	9327	5107
Kaust	5962	5399	2229	8151	9597	4758
Haql	6019	7004	1530	8697	11147	5005
Umluj	6099	6524	1787	8324	10167	4599
Western Average	6010	5909	2032	8246	9858	4687
Al Hanakiyah	6225	6292	2048	8644	10994	4920
Tabuk	6324	7372	1611	8850	11269	4981
Taif	6352	6324	2067	8565	11102	4994
Timaa	6316	7108	1731	8864	10832	4582
Average	**6304**	**6774**	**1867**	**8731**	**11049**	**4869**

In 2017, the KSA's PIF founded the National Energy Efficiency Services Co. with a capital of $600 million. The purpose of this company is to improve the energy efficiency of governmental buildings across the KSA and to assist in the promotion and establishment of a culture of energy efficiency in the KSA. This in line with the goals of Vision 2030 to have a sustainable diversified economy and environment. Moreover, the company missions will fund and supervise remodeling projects for the low efficiency government buildings and facilities. These buildings constitute 70% of total governmental and non-governmental facilities. Additionally, it is expected that these projects will help to decrease the cost of electricity in governmental buildings. By reducing this cost, the consumption of total oil that is used in power generation will also be reduced. The money saved can then be directed to replace and maintain old power system components in the generation, transmission, and distribution sectors. In addition, on March 1, 2018, the KSA standards, Metrology and Quality Organization (SASO) reviewed and modified its most important requirements of the new KSA standards for a number of electrical appliances including air conditioners, washing machines, dryers, refrigerators, and water heaters[31] – [33].

In the same year, PIF released a plan to establish a recycling waste to energy company with a clear mission to collect and use recyclable materials across the KSA. Before this, 90% of recyclable materials were sent to landfill sites that may cause long term damage to the environment. The KSA's Vision 2030 solved this issue by designing environment plans to improve recycling across the KSA. The KSA's recyclable materials are currently 50 million tons. With the new company, 85 % of these materials will be recycled and used as an alternative energy source for the industrial sector [34], [35].

III. The KSA's Location and Geography

Understanding the KSA's location and geography is crucial to discerning the future viability of alternative energy in the country. Additionally, this information can tell us what kind of future alternative energy sources may play a part in the economy. The KSAis located between 17.5◦N and 31◦N latitudes and 36.6◦E and 50◦E and longitudes. The land elevation varies between 0 and 2600m above the mean sea level [36].



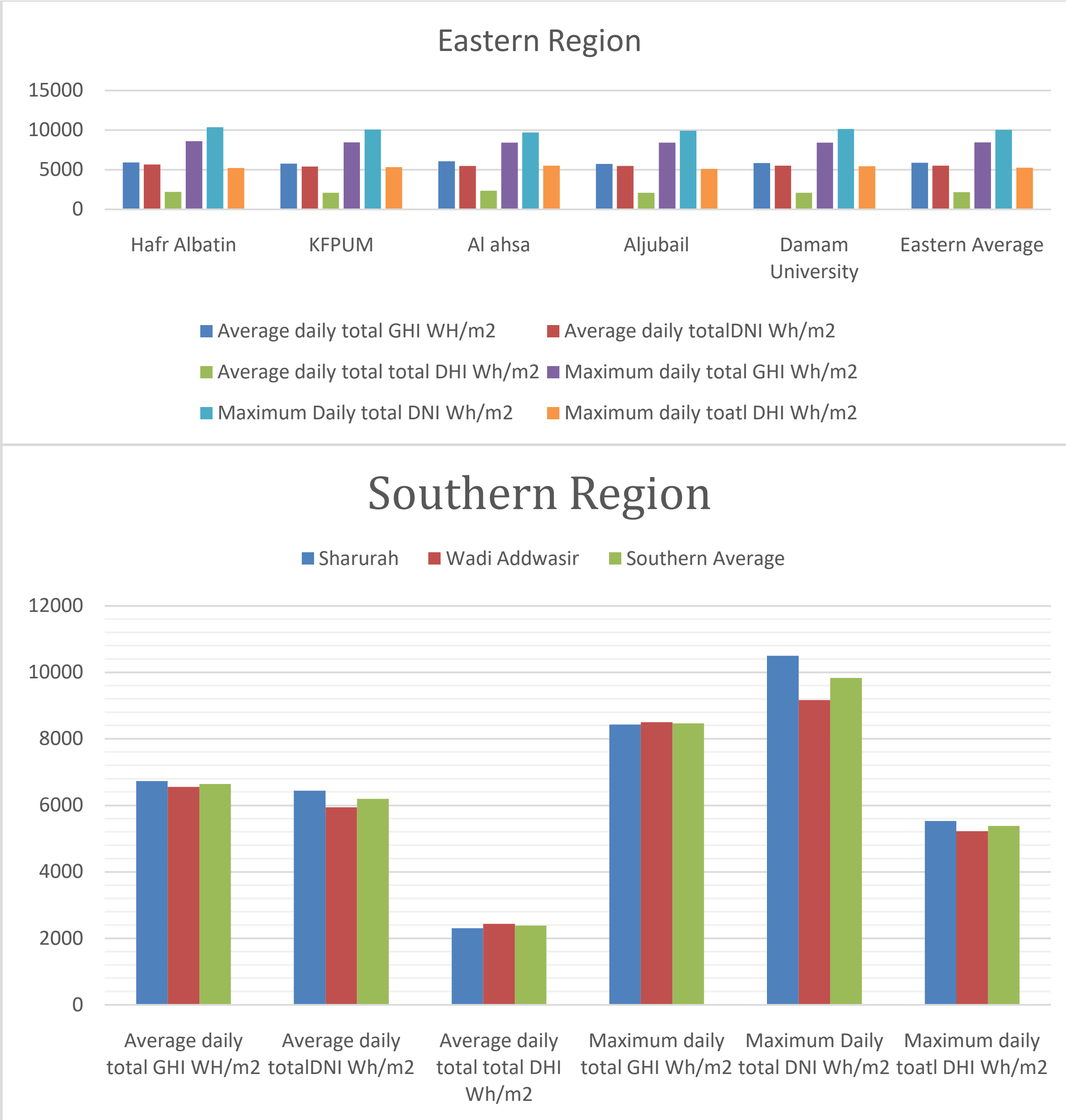
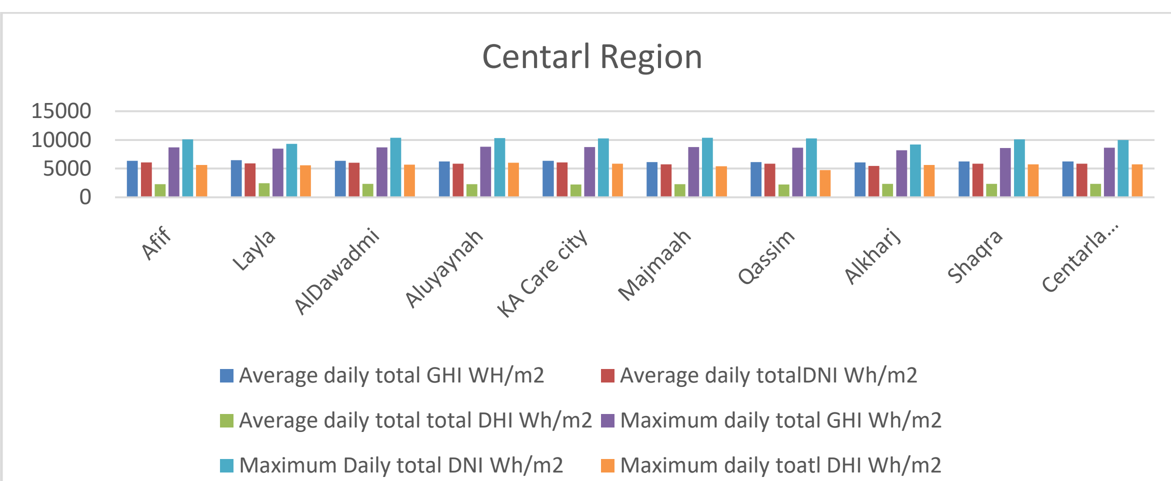


Fig. 9: Summary of the irradiation components over one year



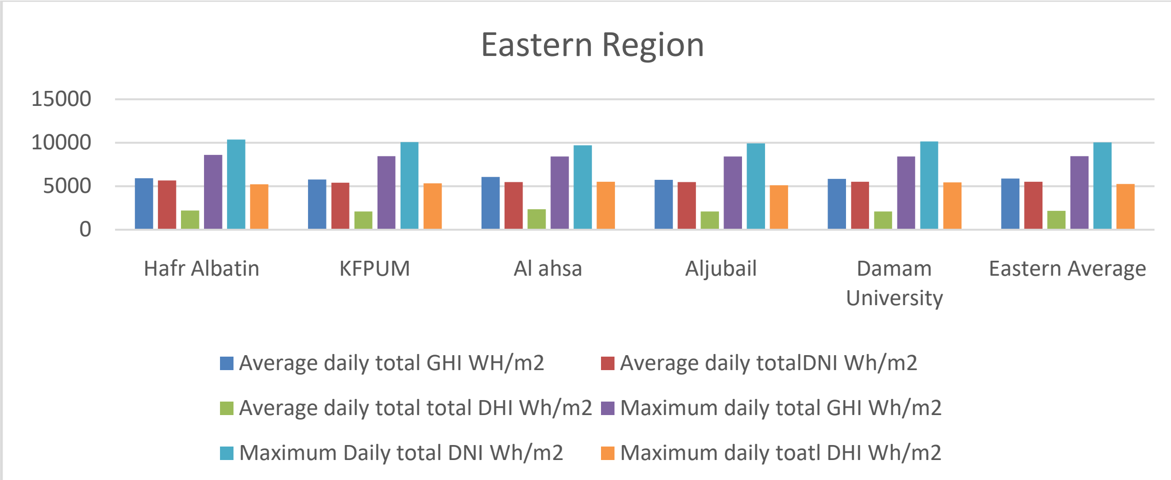


Fig. 10: Summary of the irradiation components over one year

Based on this data, the KSA is blessed in terms of its location and its suitability for diversified renewable energy resources. Most of the KSA is a perfect location for solar energy and several parts in the north are suitable for generating wind energy as shown in the map in Fig. 8 [37], [38].

Based on these two promising resources, the KSA's renewable energy program was started. A deep investigation of the renewable energy potential in the KSA was carried out. The successful use of solar modules to generate electric power by installing a solar plant depends on several factors. The first key factor is 'geographic location'. When considering this factor, the solar radiation, altitude and the height above sea level should be determined and researched to assess the expected output from the solar plant and to decide if a plant is suitable for the chosen location.

The King Abdullah City for Atomic and Renewable Energy (K.A. CARE) developed a Renewable Resource Monitoring and Mapping Solar Measurement Network to provide different environmental information to support the increasing needs of the KSA for solar power generation. This enables the application of predetermined renewable energy contribution plans in the future of the country.

By using 30 stations distributed across the country (Table 1) that include information about the latitude, longitude, and elevation of each station, the data were collected and analyzed to determine the energy available and the viability of each location as a site for solar plants [39], [40].

From the analysis of the data in Table 2, it was found that the Global Horizontal Irradiance (GHI) values are high with a low variability at all locations in the country. Apart from the temperature variations these GHI values are well-suited for strong photovoltaic (PV) technology performance at any location with a low cost of electricity. To summarize, the west part of the KSA receives solar energy of over 2473 kW h/m2/year. This is greater than the eastern sites that havea total of 2011 kW h/m2/year as shown in Fig. 10 [41], [42].

Table 3: Long-term pressure and wind speed parameters for several meteorological stations

Station	Pressure (mb) Mean	Wind speed (m/s) Mean	Wind speed (m/s) Max
Dhahran	1006.7	4.38	11.8
Gizan	1007.7	3.24	7.7
Guriat	954.8	4.22	16.5
Jeddah	1007.3	3.71	11.3
Turaif	916.9	4.33	14.4
Riyadh	942.4	3.09	8.8
Yanbu	1007.8	3.76	10.3
Abha	794	2.94	14.9
Hail	901.3	3.24	10.8
Aljouf	936.1	4.02	15.9
Al-wajh	1007.9	4.43	11.8
Arar	949.6	3.61	12.9
Bisha	884	2.47	10.3
Gassim	937.6	2.78	9.3

West and Juaymah and Dammam in the East [6]. Part of K.A.CARE's renewable energy program is the installation of 9 GW of wind power capacity by 2032.

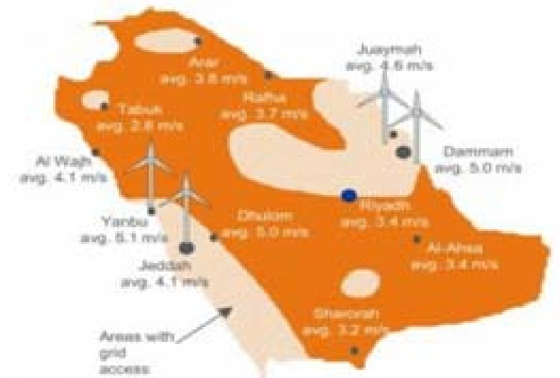


Fig. 11: K. A. CARE 9GW wind power locations map

The average wind speed in the northeast, central, and mountainous regions to the west is 33% above the levels needed for wind energy to become economically viable. The summary of average and maximum wind speed in various locations in the KSA is given in Table. 3. From these data, part of K.A. CARE's renewable energy program involves the installation of 9 GW of wind power capacity by 2032 [43].

IV. Renewable Energy Initiatives and Projects

As mentioned earlier, due to the geographical location and climate, the KSA is an excellent candidate for renewable energy projects. Moreover, in 2012the KSA was considered the seventh worldwide on the list of the 10 best places for clean energy [44]. Besides, the country's current initiatives are to promote and finance the application of renewable energy up to 2032 [45]. The KSA's past, present, and future renewable energy projects are assessed and discussed in the next sections.

a) *Solar Energy*

On an average, bright sunshine is available for 8.89 h, and the average horizontal solar radiation is 5591 Wh/m2. These figures clearly indicate that solar radiation is uniquely available in all areas of the KSA at a high intensity throughout the year. The KSA will play an effective role in the Middle Eastin providing clean energy. New and large investments in the energy sector have occurred to take advantage of the anticipated economic developments. Thus, the transformation from conventional sources to renewable needs to be verified between theory and practice by applying innovation systems (Al-Saleh, 2007; Foxon and Pearson 2008). Hence, to assess the transition from complete dependency on conventional oil to partially using renewable energy, a list of the major initiatives, programs, and projects in the solar power sector in the KSA in the past, present, and future are been discussed below:

Hysolar: In 1986 cooperation began between Germany, the USA and KSA, specifically, the US Department of Energy, the Saudi Arab National Centre for Science and Technology and the Solar Energy Research Institute. In 1991 the first part, a research and development project to study, test, enhance, and develop of hydrogen production technologies was started [46], [47].

Soleras: Established in 1975 and commenced in 1997 [48], [49] as a joint project between the KSA and the USA [50]. This project is considered among the first of its type in the Gulf region and the Middle East to study the viability of remote power not connected to a public grid. This cooperation led to the installation of the first solar-powered desalination plant in 2010 [51], [52].

Hitachi Zosen: In 2011, a contract was signed between Hitachi Zosen (Japan) and the Saline water Conversion Corporation (KSA) for 3years to reduce the production cost by exchanging expertise and knowledge and using the solar energy complex [53].

Technip E&C: A contract was signed between IDEA Polysilicon Company and Technip E & C to install the largest high-purity polysilicon for PV solar energy factory in the Middle East. Located in the province of Yanbu, this factory will be the beginning of an industrial chain in the KSA that starts with polysilicon installation and researching the needs of the KSA energy market and will end with meeting the growing demand for electricity [54].

Kyoto Protocol: In 2005 and 2011, the KSA submitted its vision and strategy for the reduction of greenhouse gas emissions as a member of the global community [55]. To achieve this, the KSA will promote the utilization of renewable energy sources to reduce CO2 emissions in line with the Kyoto protocol. The KSA showed its commitment to policies and measures to reduce CO2 emissions [56].

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Conergy: In 2010, cooperation commenced between two leading solar system companies: Conergy (Germany) and Modern Times Technical Systems (KSA). A 200kW solar plant was installed in Riyadh and another 330 MWh plant will be installed in the King Abdullah Financial District to power the main computers outside the national grid [57].

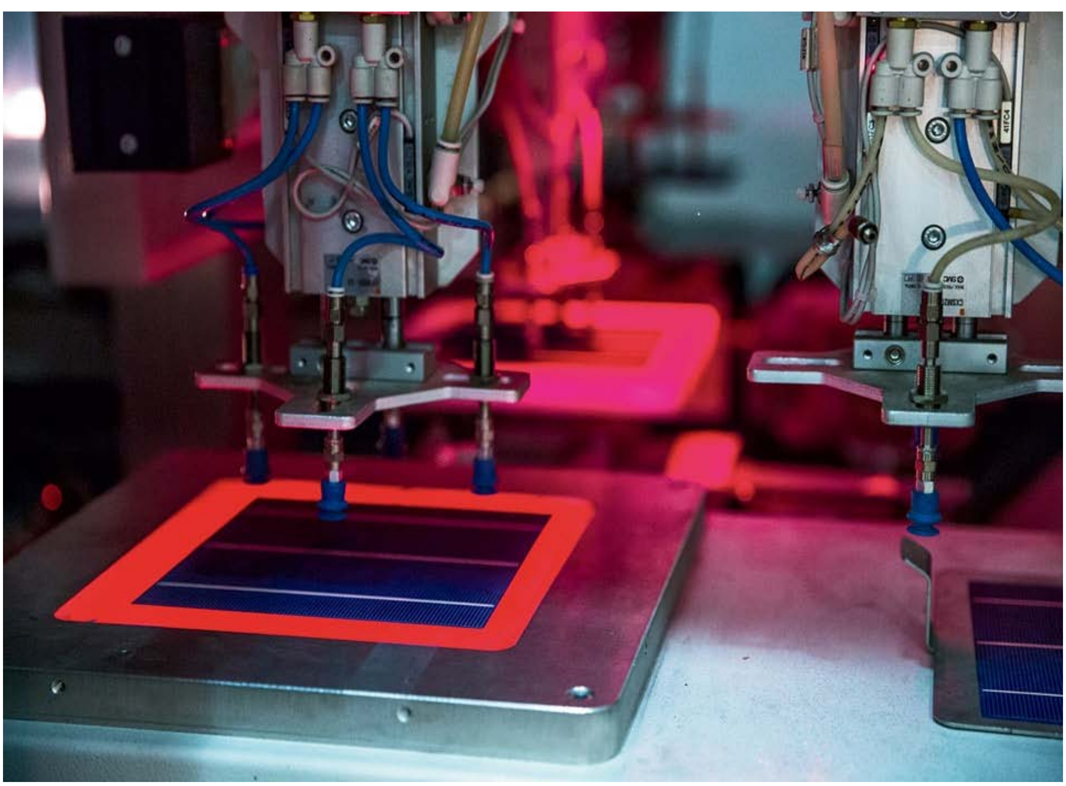

Fig. 12: PV factory in the KSA

Association of California Water Agencies (ACWA) & Canadian Ministry of International Trade (CMIT): A joint cooperation between CMIT, ACWA, and K. A. CARE to establish several solar plants in 6 provinces. Meanwhile, ACWA is seeking an opportunity to take part in renewable energy projects worth $7.4 billion [58], [59].

NYSE-IBM: Based on the KSA's plan to reduce the cost of water desalination by reducing the energy and water cost, a research collaboration between IBM and KACST was signed to power the desalination plants by solar energy [60].

General Electric (GE): In 2014, the Saudi Electricity Company (SEC) signed a contract with GE worth $1.2 billion to establish conventional and solar power plants in the Tabuk region [61].

Fig. 13: Al Khafji water desalination site

Electricite de France (EDF) & Reactor builder (Areva) France: In 2017, EDF and Arevaheld talks about taking part in the KSA's new nuclear power plants under the KSA's program of building a 17 GW nuclear power station by 2032 [62].

Manz AG: As one of the largest solar high-tech companies worldwide and attracted by the high potential of theKSA's solar energy market, the company aims to build solar plants or manufacture solar modules [63].

Soitec: In 2016, Soitec cooperated with Khaled Juffali Company (KJC), a Salam and Khan local firm in the KSA, to increase the local contribution to solar systems by manufacturing the PV modules in the KSA [64].

Based on cooperation between the KSA's governmental and non-governmental agencies with the international renewable energy research and development sectors, 50 years' worth of solar energy projects have begun in different regions in the KSA. With sponsorship the KSA now has full information on renewable energy resources and viable locations for solar and wind power stations. Several factories for silicon or PV modules have been established to boost the local market and the energy sector. The following list concerns the trend and gradual development of solar energy projects in the KSA:

Last Century

- In the 1970s and the 1980s, KACST commenced renewable energy research and development projects and continued plans to develop the solar energy sector [65].
- In 1984, Soleras established a solar thermal seawater desalination pilot plant in Yanbu. However, due to financial reasons, the project was not completed[66].
- In 1994, KACST commenced the establishment of an Atlas for solar energy jointly with the US National Renewable Energy Laboratory (NREL–USA). An example of this was the PV powered water desalination station the village of Sadous [67].
- In 1996, KACST started forced closed type solar water heating systems for the local market. More than 1100 rooftop solar collectors have been installed on 380 residences in KACST's campus in Riyadh [68].
- During the 1990s, KACST began a solar radiation assessment in cooperation with NREL to improve the solar resource assessment capability by installing a high-quality 12-station network for monitoring all parameters that affect solar energy, such as irradiation and diffuse radiation, among others [69].
- To study the reliability of the PV modules in the KSA's weather conditions, a 3 kW PV system was used at the solar village site with different orientations in the four axis to evaluate the best orientation, reliability, the effects of fine dust, the performance and efficiency at different temperatures [70].

21st Century

- In 2000, an initially joint research program with Germany was established to produce 100kW using two solar thermal dishes.
- HYSOLAR established a 350kW solar hydrogen production plant to verify the safety and reliability of using solar energy in producing hydrogen.
- To reduce the cost of extending power lines to remote areas, KACST has installed PV lighting and power systems to power highway devices in two isolated tunnels in the southern mountains.
- In cooperation with international partners, the Ministry of Agriculture and Water have carried out several experiments to date into the most efficient solar power techniques. These experiments were conducted at Al-Hassa and Qatif Agricultural experimental sites.

Fig. 14: Duba power station

Fig. 15: Waad Al Shamal solar power plant

- KACST established a demonstration station in Sadous village for a PV-based water-pumping and desalination system. The station is used only for research and development.
- In 2009, KACST and IBM started a program with the supervision of the KSA's universities and research centers to conduct research into the feasibility of using solar power instead of conventional oil in water desalination applications to reduce the oil consumption. In 2010, KAUST in Thuwal installed its first large-scale roof mounted PV system at the KAUST campus with a 2MW power output in cooperation with Conergy. It consists of 9,300 solar panels of 215 W with a total covered area of 11,600 m2and an annual output of 3,281 MWh.

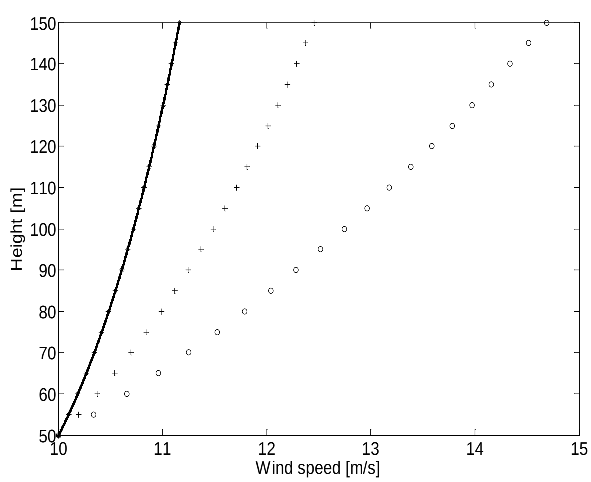

Fig. 16: Vertical wind speed profile

- The world's largest solar thermal plant at 36,305 square meters on the roof of the Princess Nora University in Riyadh was commissioned. Solar Frontier has completed 1 MW CPV power plant at the Nofa Equestrian Resort, near Riyadh. In April 2012, a $11 billion solar heating project with an installed capacity of 25 MW was established to meet the hot water needs of all the 40,000 students on the campus. The solar water heaters are mounted on the roofs of the university buildings with total collector surface area.
- One year later, the first large-scale, 500 KW, PV power system was commissioned in the KSA.

- In 2012, the King Abdullah Financial District installed 200-KW rooftop PV systems to obtain the US Green Building Council, i.e., the top eco certificate worldwide.
- Al Khafji Solar Powered Desalination Plant: In January 2015, a contract was signed between Advanced Water Technology and Abengo to build the world's largest solar energy-based desalination water plant. The total cost is $130 million, and the plant started to supply the Alkhafji area from April 2018 which is shown in Fig. 15. The plant provides 60,000m3 of desalinated water each day to the city.
- In 2014, a research team from KACST began working on developing cost-effective solar cells made from silicon and gallium arsenic in two different desalination projects.
- In 2013, Jeddah Municipality launched its first pilot project in Ruwais to provide street lighting using solar energy (Arab News 2015).
- The Yanbu Plant project on the west coast completed its third phase and is expected to generate 2650 MW of energy for Madinah and its surroundings villages.

Table 4: Solar energy projects in the KSA

Period or year conducted	Location	Description of projects		Application purposes
		Type	Capacity	
1981–1987	Solar Village	PV system	350 kW (2155 MWh)	AC/DC electricity for remote areas
1981–1987	Saudi universities	Solar cooling	–	Developing of solar cooling laboratory
1986–1991	KAU, Jeddah	Solar hydrogen	2 kW (50 kWh)	Testing of different electrode materials for solar hydrogen plant
1986–1994	Solar Village	Solar-thermal dishes	2 pieces, 50 kW	Advanced solar stirling engine
1987–1990	Solar Village	PV test system	3 kW	Demonstration of climatic effects
1987–1993	Solar Village	PV hydrogen production	350 kW (1.6 MWh)	Demonstration plant for solar plant hydrogen production
1988–1993	Dammam	Energy management in buildings	–	Energy conservation
1988–1993	Al-Hassa, Qatif	Solar dryers	–	Food dryers (dates, vegetables, etc.)
1989–1993	Solar Village	Solar hydrogen generator	1 kW (20–30 kWh)	Hydrogen production, testing and measurement (laboratory scale)
Since 1990	Solar Village	Long-term performance of PV	3 kW	Performance evaluation
1993–1995	Solar Village	Internal combustion engine	–	Hydrogen utilization
1993–1997	Solar Village	Solar collectors development	–	Domestic, industrial, agricultural
1993–2000	Solar Village	Fuel cell development	100–1000 W	Hydrogen utilization
1994–1999	Sadous Village	PV water desalination	0.6 m^3	PV/RO interface per hour
1994–2000	12 stations	Solar radiation measurement	–	Saudi solar atlas
1994–2000	5 stations	Wind energy measurement	–	Saudi solar atlas
1996	Southern regions of Saudi Arabia	PV system	4 kW	AC/DC electricity for remote areas
1996	Muzahmia	PV in agriculture	4 kWp	AC/DC grid connected
1996–1997	Solar Village	Solar-thermal desalination	–	Solar distillation of brackish water
1996–1998	Solar Village	PV system	6 kW	PV grid connection
1999–2000	Solar Village	Solar refrigeration	–	Desert application

- Makkah municipality is building a solar plant worth SR 2.4 billion to supply 35 tunnels and streetlights in the holy city to save electricity and serve as an alternative energy source.
- Madinah Municipality is also using solar power to light public utility gardens, parks, and streetlights in the city to reduce electricity consumption and greenhouse gas emissions equaling 35 tons of CO2.
- Madinah's Taibah University has developed an efficient photosynthesis system to pump water from wells using solar energy.
- In 2017, the construction of a solar power plant in Makkah started under the supervision of the Ministry of Islamic Affairs, to switch to solar energy usage in mosques to heat water for ablution and AC systems with a cost of $640 million and a capacity of around 100 MW. The project is expected to be completed by the end of 2018. The output energy of this project is 385GWh per year and it will reduce the cost of electricity by $587 million.
- In early 2017, the KSA launched the first construction phase of the Green Duba generating power station. This plant is the largest power project in the Middle Eastand has a cost of $1.2 billion, which is shown in Fig. 16. Duba city is located at the northwest of the KSA where solar irradiation is promising for solar energy projects. Hence, the station capacity is over 605 Megawatts, including 50 Megawatts derived from solar energy. Over 600,000 houses will be powered by this plant for a year. Moreover, it is expected to have an energy surplus that can be exported to the world.
- In April 2015, construction of a 1,390 MW power plant began at Waad Al Shamal. 50 MW of this power will be solar energy. The plant will provide electricity for more than 500,000 houses. The project costs $1 billion, and it is expected to be completed by the end of 2018.
- Table 4 lists all the solar projects in KSA.

b) *Wind energy*

Wind energy systems are used to extract the dynamic power of wind and convert it into electrical energy. The air dynamic energy of mass m moving at speed can be written as [71]:

$$E_k = \frac{1}{2} m \upsilon^2 \quad (1)$$

During a period, *t*, the mass of air with the same speed and density ρ pass through an area *A* can be written as:

$$m = \rho A \upsilon t \quad (2)$$

The wind power is then calculated from equation (1) and (2) [72]:

$$P = \frac{1}{2} \rho A \upsilon^3 \quad (3)$$

It is obvious that the wind power depends on the wind site characteristics and the cube of the wind speed. The turbine blade power is less than the mechanical power by the power conversion coefficient C_P and the rotor power can be expressed as[73]:

$$P = \frac{1}{2} \rho A \upsilon^3 C_p \quad (4)$$

C_P is in the range of 0.2 and 0.5 for any number of turbine blades.

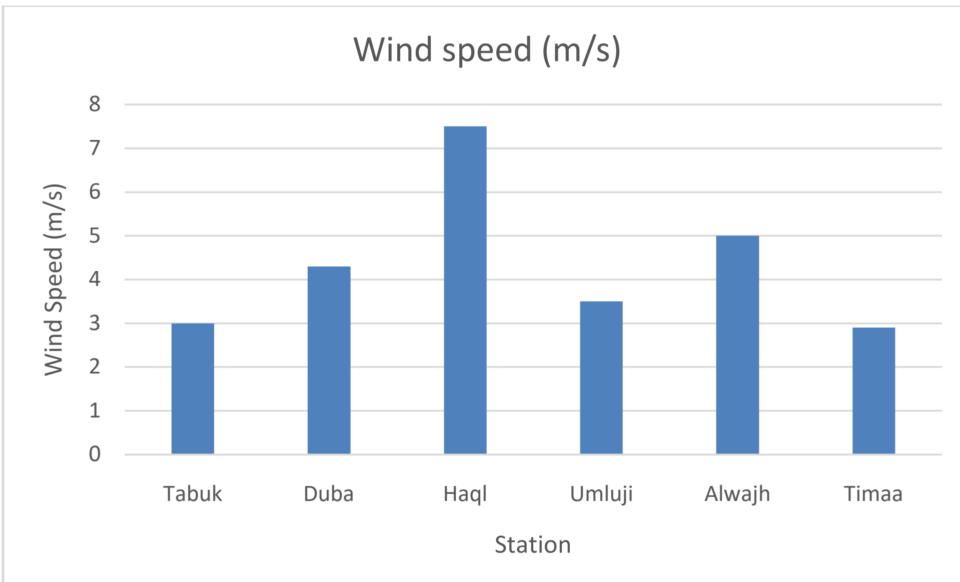

Fig. 17: Average wind speed at a height of 10m for all stations

Based on the height, the wind speed changes as following [74]-[76]:

$$\frac{\upsilon_2}{\upsilon_1} = \left(\frac{h_2}{h_1}\right)^{\alpha}, \quad (5)$$

where *h* is the height of point under consideration, *υ* is the corresponding wind speed and α is the empirical parameter that depends on the terrain roughness and its range varies as in [77].

The theoretical vertical wind speed profile for a site with a mean wind speed of 10 [m/s] at different surfaces is shown in Fig. 17.

From the equations, the extracted power from the wind depends on the height of the hub and cubic of the wind speed. By increasing the hub height and selecting a high average wind speed, the output power will be increased.

Wind energy utilization is the second promising source of renewable energy in the KSA. The importance of wind power as an alternative energy source emerged after intensive studies on wind resource assessment and its viability in separate locations. Beginning in 1986, a plan was established for a wind atlas by using the measured wind speed at low heights from 8 to 12 m above the ground level for 20 separate locations in the KSA[78]-[83]. During the period 1970–1982, wind characteristics data such as the average wind speed and direction were measured for 24 hours to develop a wind atlas. This atlas was incorrect due to the low heights of 8 to 12 m that were used to measure the wind data. In addition, the sites were selected randomly and were located near turbulent sites like airports. In 1996, new heights of 20, 30 and 40 m were selected to measure the wind speed average values and directions in separate locations in the KSA [84]. For accurate and reliable results, [85]used six anemometers in every wind tower, with two anemometers placed at each of the three heights. The annual average wind speed at 40 m at separate locations was found to be between 4 and 5.3 m/s at most sites [86]. The average annual energy was measured around the KSA and it was found that the energy yield is 120,000 MWh/year from 40 1500KW wind turbines in a 60 MW wind farm [87]. Due to the potential of the Tabuk region as a windy onshore location, the potential of wind energy in this region has been assessed. The averages of annual wind speeds at a 10m height for various locations are shown in Fig.20 [88]. The annual average wind speed at Haql is 7.5 m/s and this makes it a particularly good site. Additionally, the AlWajh site has a significant wind speed of 5.04 m/s. The other sites are not suitable for wind energy generation. The seasonal variation of monthly mean winds at10m for all stations is shown in Fig. 21.

To assess the selected site's wind characteristics at the different hub heights, the average wind speed at 30,40,50,80 and 100m hub heights were measured as shown in Fig.22.

To have a steady source of wind energy, wind speeds more than 4.5 m/s are considered acceptable in the wind energy assessment. It is noted that the wind speeds at the Haql and Al Wajh sites have average values more than 4,5 m/s at 10m [89]. The wind speeds at the Duba site have values more than 4.5 m/s at a height above or equal to 20m. On the contrary, the Tabuk, Umluj, and Timaa sites do not show wind speeds greater than 4.5 m/s at 100m. However, at the Haql site, the average wind speeds rise to 8.27 m/s at 20 m. The maximum wind speed that can be obtained at 100m is 10.5 m/s meaning the Haql site is a suitable location for wind power plants. In conclusion, wind turbines with high hubs can be used to generate power in the Tabuk region.

Between 1980 and 2012 studies of 20 promising locations were carried out. The data collected from 20 meteorological stations was then analyzed [90]. Samples of the updated and revised data including the pressure, average and maximum wind speeds for the different sites are listed in Table 4.

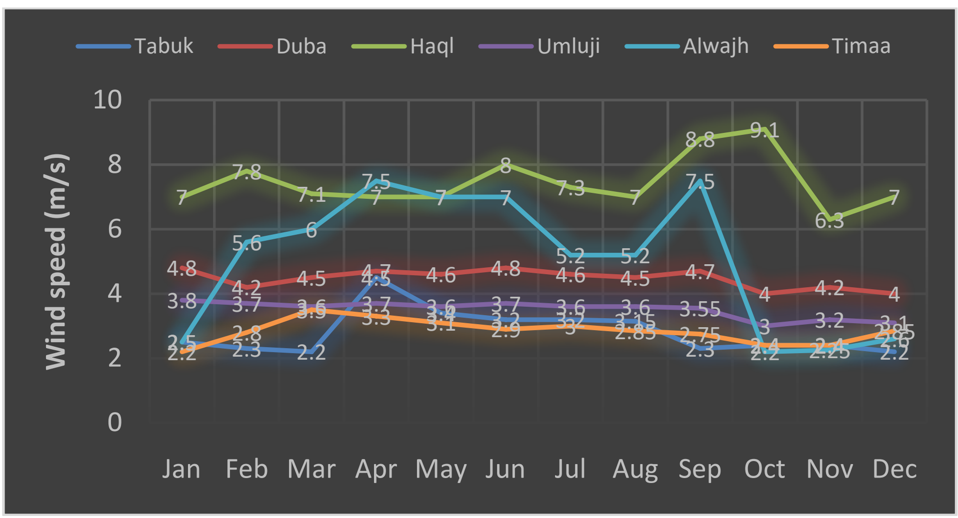

Fig. 18: Seasonal variation of monthly mean winds at a height of 10m for all stations

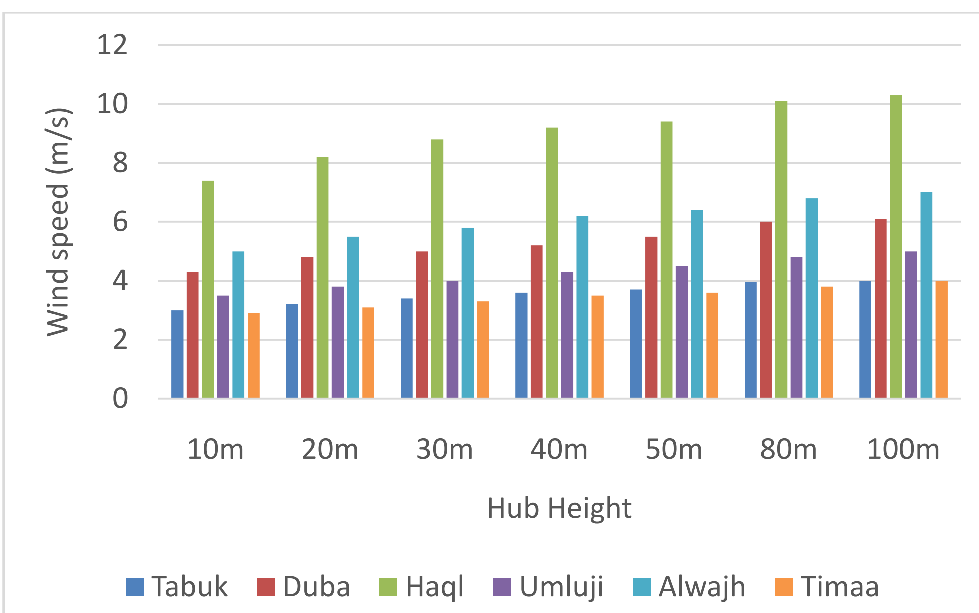

Fig. 19: Extrapolated wind speed values at different heights

It is noted that the maximum wind speed is 16.5 m/s at the Guriat station, while the minimum wind speed is 7.7 m/s at the Jizan station. The maximum average wind speed is 4.43 m/s at the Alwajh station, while the minimum wind speed is 2.1 m/s at the Nejran station. Previous studies have shown that these wind generators are efficient at 4.5 m/s or higher.

The cities of Dhulum and Arar are potential sites for off-grid, remote wind turbines and they also proved the viability of using grid-connected wind turbines to partially power the two coastal cities of Yanbu and Dhahran [91]. KAPSARC found that the wind speed varies significantly from region to region and from season to season [92]. When the wind speeds are measured in a 3-hour period between 14:00 to 17:00 across all regions and seasons, the highest wind speed of 8 m/s is found in the eastern region in spring and fall. In summer, the highest wind speed in the eastern region is 6.7 m/s; in winter, the highest wind speed is 7.4 m/s [93].

The largest wind energy project in the KSA presently is the Dumat Al Jandal wind power project in the Al Jouf region. The Renewable Energy Project Development Office of the KSA's Ministry of Energy, Industry and Mineral Resources is implementing the project. The 400-MW Dumat Al Jandal wind power project is part of the first round of the National Renewable Energy Program that seeks 9.5 GW of renewable energy by 2023. The second round will also be 400MW but the location has not yet been determined. However, it will be at one of the circled sites shown below [94].

Fig. 20: Wind power project in Wadd Alshamal, KSA

c) Biomass

Biomass power generation was first used in Denmark in the 1970s during the global oil crisis. Denmark started various renewable energy projects including systems to convert straw and waste to energy. Biomass technologies have been developed in different countries and presently represent 14 % of the world's final energy consumption [95]. By 2050 it is expected that 50 % of the world's primary energy use will be from biomass generation [96].

During 2014, 15.3 million tons of Municipal Solid Waste (MSW) was produced in the KSA, with an average daily rate of 1.4 kg per person[97]. By 2033 MSW is projected to be 30 million tons per year due a 3.4% growth in population. Currently, the collected MSW is sent to landfills. There is some sorting and recycling of paper and cardboard but this is a small percentage of the total MSW produced [98]. To contain this large amount of waste (up to 2.8 million m2/year), there is a high demand for new landfills. These waste management practices will become aserious public health and environmental issue if no action is taken to recycle part of this waste

Therefore, the KSA considered the generation of electricity from MSW as a part of the shift from conventional oil to renewable energy. There are primarily five wastes to energy technologies widely used and implemented for MSW management, namely incineration with energy recovery, pyrolysis or gasification, plasma arc gasification, refused derived fuel, and biomethanation.

It is estimated that 250 – 300 tons per day waste-to-energy plant can produce around 3 – 4 MW of electricity [99] and a network of such plants in cities around the country could also make a difference in waste management.

KSA's 2030 vision [100] put forward a strong regulatory and investment framework to develop the KSA's waste to energy sector. By 2025 an ambitious target of 3GW of energy from waste is to be achieved.

d) Geothermal

Geothermal power is generated by heat due to elevated temperatures in the Earth and can be used as a direct source of electricity. The geothermal heat gradient increases with depth and pipes can be extended into the Earth to several kilometers to circulate water that is converted to steam on its way out to the surface as shown in Fig. 17. Throughout history people have used geothermal heat in a simple direct way for baths and spas due to their beliefs of the healing effects of this hot water. Presently, geothermal energy is widespread in a variety of forms. The main types of geothermal direct applications, with the percentage of total installed capacity attached; are bathing/ balneology at 19.1%, space heating at 15.4%, greenhouses at 5.0%, geothermal heat pumps at 54.4%, industry at 1.7%, aquaculture at 2.2%, agriculture at 0.6%, cooling or snow melting at 1.3% and other uses at 0.3% [101].

The KSA has rich geothermal features, with 10 hot springs discovered in the regions of Gizan and Al Laith in the southern part of the country[102]. In addition, a large volcanic region is being explored in the western part of the KSA. Nonetheless, research into the geothermal potential in the KSA is not proportional to the availability and the abundance of geothermal power [103], [104].Even though geothermal resources may be the least potential source for renewable energy in the KSA, the necessity for achieving sustainable development in terms of energy calls for a serious exploration of all viable options.

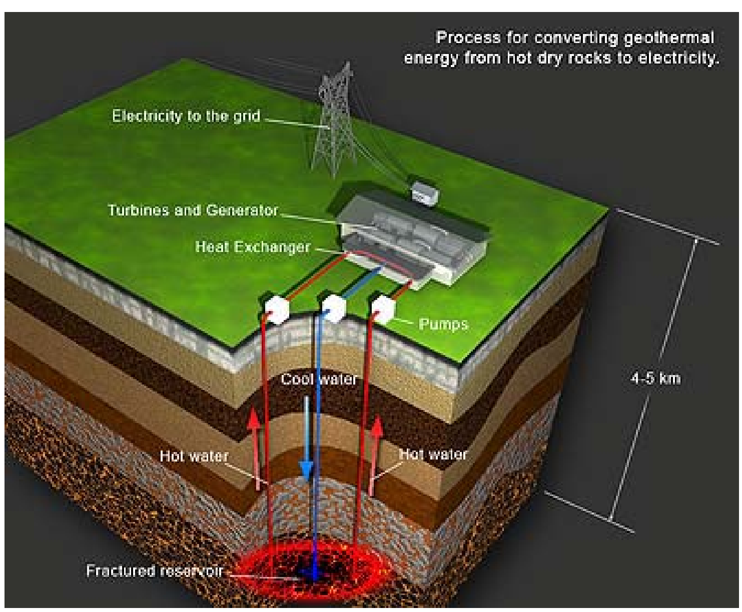

Fig. 21: Geothermal plant

V. Potential Benefits of Renewable Energy and Energy Efficiency

Implementing the KSA's national renewable energy plans and objectives could have a significant impact on the whole region as following:

Minimizing CO_2 emissions: According to the World Resources Institute, the KSA's emissions are 594.71 million tons of CO2 per year, which is 1.4% of the world's total emissions [105]. Using renewable energy sources will decrease these emissions. For example, a solar plant with an estimated power plant area of 1.25 km2 has a capacity of 20 MW and generates about 200–300 GWh/year. This would save 500,000 barrels of oil and avoid 200,000 tons of CO2 emission per year in the KSA[106].

In 2015, the KSA submitted its INDC to the Paris climate summit that seeks to avoid emitting up to 130 million tons of CO2 by 2030 (UNFCCC). This target can be achieved in four ways: the use of renewable energy, energy efficiency, carbon capture and storage, and public transport.

Job creation: One of the most important benefits of renewable energy is job creation. It is a component of the socio-economic benefits that emerge from the establishment and spread of renewable energy and energy efficiency technologies. By achieving the KSA's targets, more than 137,000 direct jobs are expected to be created [107]. By 2030these numbers could reach more than 430,000. Most of these jobs will serve the community and reduce the unemployment rate.

Creation of a local renewable value chain: Several countries have adopted such a policy by including local content requirements for the equipment they use in several industrial sectors. The KSA designed its renewable energy and energy efficiency to boost the local renewable value chain and attract foreign direct investment in the KSA, bringing prosperity to our citizens as part of the goals established in Vision 2030.

VI. Challenges for Solar Energy Development in the KSA

a) Technical barriers

Inadequate technology and a lack of the infrastructure necessary to support these technologies present the main technical barrier to the development of renewable energy. The lack of physical facilities for the transmission and distribution networks, as well as the equipment and services necessary for power companies is a major infrastructural challenge for renewable energy development in most developing countries. Also, a lack of trained personnel to demonstrate, maintain, train, and operate renewable energy structures, especially in regions with low education levels, mean that people are unwilling to import the technologies for fear of failure.

Moreover, as in all countries, parts of the KSA's utility-grid are outdated and inefficient. Old transformers, transmission lines, and other infrastructure will be replaced to save energy. The replacement and addition of more equipment will be completed by 2020, with $4 billion invested in distribution projects annually[108] – [110].

b) Socio-cultural barriers

A review of the impact of socio-cultural barriers to using renewable energy reveals several factors; for example, households' unwillingness to adopt renewable energy for fear of unreliability forms, as one of the basis for failure to adopt renewable energy technologies in some countries. For example, public disinterest and disengagement in wind energy development were identified as the main social issues hindering renewable energy development in Saskatchewan, Canada [111].

Further, another challenge to development is a lack of knowledge and awareness of renewable energy technologies and systems among rural communities. For example, many people in Sub-Saharan Africa are uneducated and, therefore, they do not understand the concept of renewable energy. These uneducated people in the region do not understand the technical and environmental impacts associated with over-use of combustible fuels [112]. Taken together these factors have reduced the rate of development, circulation and usage of renewable infrastructure and technological knowledge. Therefore, the KSA should ensure the creation of awareness of renewable energy among communities and a critical focus on their socio-cultural practices are in place.

VII. Conclusions and Recommendations

The KSA has a great natural potential for renewable energy resources and an ambitious national plan to boost the contribution of renewable energy to meet the domestic electricity demand. In this regard, the KSA has taken a crucial step in the development of renewable energy projects with a focus on solar power by 2030. A comprehensive investigation of the past and present status, and the future direction of renewable energy in terms of solar desalination, solar hydrogen production, solar and wind power generation is presented. The barriers to renewable energy development are also presented such as the lack of a skilled workforce, social awareness, and outdated segments of the power grid.

Throughout the review, it was obvious that there are several KSA commitments both to the Vision 2030 and the national transformation programs to re-position the country on the path to sustainability. These commitments emerge from different factors such as rapid population growth, water desalination demands, the excessive consumption of crude oil, a low energy efficiency in buildings due to the heavy use of AC, the desire to increase the domestic resident employment levels and the high emissions of CO_2.

Simultaneously, the KSA authority aspires to have a greater energy diversification – this provides an added push for the growth of renewable generation capacity. Currently, renewables seem poised to move from peripheral applications (such as remote areas or research sites) to the mainstream utility-scale electricity markets, creating diffuse economic, social, and environmental benefits in the process.

In this regard, the KSA has taken steps to shift its dependency from oil to solar, wind and nuclear sources of energy, and plans to secure half of the country's electricity needs from alternative sources of energy in the next 20 years. The government has announced an ambitious plan to install 54 GW (including 41 GW of solar power. and 13 GW of wind) of renewable energy and invest totally $108.9 billion by 2032. To execute this plan, the KSA has cooperated with different governments, institutes, and companies. Starting with cooperation with Germany and the US department of Energy in 1986, this has developed projects of water desalination, electricity generation and agricultural applications. To strengthen the information about renewable energy resources in the KSA a collaboration with US (NREL) for establishing the Solar Radiation Atlas began in 1986. More cooperation with the USA, Canada, Japan, and France to exchange expertise knowledge has established a solid foundation for the development of renewable energy. The KSA now has several prominent energy institutes who led the planning and implementation of the transition from oil to renewable such as K. A. CARE, KACST and NERP. These institutes have determined the KSA's energy policies and sustainable economic and societal plans. Before 2000, small-scale renewable energy projects such as the installation of 1100 solar flat plate collectors on the roof of one building in KACST, a 350 KW solar production plant, and A 3 kW photovoltaic power system were developed to evaluate their reliability, performance and efficiency in the KSA environment.

After providing a route to implement the plans and policies and gathering information about the wind and solar energy potential in all regions, and creating the necessary centers to implement the KSA's orientation, a major plan was announced to start the transition to a sustainable economy and society. Based on this plan several mega projects have begun such as a large-scale solar system of 2 MW on the roof of KAUST, installation of 120 wind turbines of 2.75MW in Huraymila, 80 km north to Riyadh, in January 2017, a solar plant of 25MW in Princess Nora University, a wind farm of 400MW in the north part of the KSA, the commencement of a solar plant with a 100MW capacity at a cost of $640 million in Makkah in 2017, and a 1,390 MW solar power plant of 1,390MW at a cost of $1 billion launched in Waad Al Shamal to be completed end of 2018, as shown in fig. 17 and Fig. 22.

With these projects, more jobs are to be made available in this sector with 95% of employees created being KSA nationals. Meanwhile, K.A. CARE, KACST, the SEC and Saudi Aramco, along with the manufacturing and delivery of modules, are also working on the knowledge to be transferred to semi-government and private sectors to establish fully integrated manufacturing facilities.

The new Vision 2030 increases the public–private collaboration in this regard and will assist in creating a public–private partnership in the KSA.

From January 2018, electricity tariffs were increased to 5, 10, 18 ha/kWh for different consumption categories. This produced two major impacts: an increase in the monthly bill and a corresponding reduction in the consumption. At the same time, the increased tariffs will impact the small-scale PV system, for example, the payback period will be ~5-7 instead of ~10-15 years, which is attractive considering the 25-year lifecycle of the system.

Expanding the use of PV solar plants will cause the PV price to drop. This will result in solar energy becoming feasible, cost-effective and competitive. Globally, the cost of the construction of wind and solar power projects has been reduced by 20 and 60%, respectively.

However, there are key challenges relating to economy and efficiency. Fortunately, there are 6 key drivers that will accelerate the adoption of this technology:

- Net-Metering Regulations: Net-metering is an enabling policy designed to foster private investment in renewable energy. In August, the Electricity and Cogeneration Authority issued a regulatory framework for electricity consumers to operate their own, small-scale solar power (<2 MW) generating systems and export any unused power to the national grid, offsetting this amount against their own consumption. This creates a significant financial incentive and accelerates private sector investment in small-scale renewable energy applications. This will come into force in July 2018 and pre-qualified, registered installers must carry out the work for the system to be eligible.
- Feed-in tariff: Feed-in tariffs are increasingly considered to be the most effective policy for stimulating the rapid development of renewable energy sources and are currently implemented in many countries. They have consistently delivered new renewable energy supplies more effectively, and at lower cost, than alternative policy mechanisms. The central principle of feed-in tariff

policies is to offer guaranteed prices for fixed time periods for electricity produced from renewable energy sources. To encourage investment, the KSA announced that it will move quickly to feed-in tariffs to build out the program. 90% of the capacity will be assigned through the application of technology-differentiated feed-in tariffs.

- Fossil fuel quota and renewable energy incentives: KSA should launch guidelines, incentives, or regulations that certain industries must have 10%, or even 20%–30%, of their energy from renewable sources. Also, a quota system will ensure the success of green certificates by encouraging all generators to develop new renewable sources and reduce the wastage of existing renewable. Taxing large companies, factories, and institutions can implement this when they use a certain percentage of fossil fuels(e.g., 90%).
- Private investors: K.A. CARE suggested that private investors share and participate in building, operating and owning the solar and wind plants for 20 and 25 years, depending on the nature of the project. The proposal states that the government will not own the plants.
- Integrated local renewable energy industry: To help reducing the payback period and increasing employment, a complementary industrial sector should consider and make policy for regulating the contribution of the private sector.
- Solar Technology Advancement: Two challenges that limit the efficiency of the PV panels are dust and elevated temperatures. Research has been conducted into solutions to overcome these challenges such as electrodynamics screens, coatings and air blowers. These advancements will maximize the efficiency and output of solar solutions, while yielding significant financial gains and accelerating their wide-scale adoption.

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Optimization of Wind/Photovoltaic Hybrid Renewable Energy Systems for Telecommunication Networks in Nigeria

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Keywords: optimization of wind, hybrid renewable energy systems, telecommunication networks in nigeria.

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I. Introduction

a) Background of Study

Energy is the ability to do work; and it is fundamental to mankind, because human activities depend on one form of energy or another. Energy sources can be classified into renewable and non-renewable. Nigeria is country rich in both renewable energy and non-renewable energy resources for electricity production. However, aalmost all energy consumed in Nigeria comes from non-renewable energy sources such as coal, natural gas, and oil.

Despite the abundance of these energy resources in Nigeria, the country is in short supply of electrical power. Only about 60% only of the nation's over 199 million has access to grid electricity and at the rural level, where about 70% of the population live, the availability of electricity drops to 15%. Nigeria requires per capital power capacity of 1000 Watts per person or power generating/handling capacity of 170,000 MW as against the current capacity of 7000 MW. This will put Nigeria slightly below South Africa with per capita power capacity of 1047 Watts, UK with per capita power capacity of 1266 Watts and above Brazil with per capita power capacity of 480 Watts, China with per capita power capacity of 260 Watts. Okafor and Uzuegbu (2018)

Currently Nigeria has per capita power capacity of 32.57 Watts and this is grossly inadequate even for domestic consumption. A high proportion of Nigerian's total energy output is still generated from fossil fuels such as oil and coal, which are treats to the environment due to emission of carbon dioxide. Okafor and Uzuegbu (2018).

It can be said that with figures given Nigeria as a developing country is faced with serious energy crises. Nigeria has been unable to meet the energy needs of their citizens. But, in developed countries, the use of non-renewable energy sources for electricity has been reduced from year to year in advanced countries. So there is a need to find another source to produce stable electricity generation in Nigeria. To achieve the goals of development, a strong energy sector is essential. In a quest to realize this, there is need to turn to different sources of energy which among them are renewable energy sources.

With the continuous increase in energy demand (particularly the electricity), and its environment concerns, the development of alternative energy resource to the conventional fossil generation has become a critical topic world widely and cannot be over emphasised.(Maczulak, 2010) and (Anaya-Lara, 2009).

In Nigeria for instance, Okafor and Uzuegbu (2018) including other experts in the field of energy resources for electricity generation, offer the following as solutions to resolving the challenges facing successful renewable energy adoption in Nigeria. The development of renewable energy services is linked to many other sectors such as telecommunication, agriculture, small scale industrial enterprises and poverty alleviation, thus it is recommended that, renewable energy related projects have a greater likelihood of success if implemented in tandem with activities in these sectors to ensure sufficient demand for the energy services providers.

The Federal Government approved the National Energy Policy (NEP) in 2003 to articulate the sustainable exploitation and utilization of all viable energy resources. The policy is hinged on private sector development of the energy sector. The key elements in the national

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policy position on the development and application of renewable energy and its technologies are as follows (Balaet al, 2000):

1. To develop, promote and hardness the Renewable Energy (RE) resources of the country and incorporate all viable ones into the national energy mix
2. To promote decentralized energy supply, especially in rural areas, based on RE resources
3. To de-emphasize and discourage the use of wood as fuel
4. To promote efficient methods in the use biomass energy resources
5. To keep abreast of international developments in RE technologies and their applications

Relying in this framework, renewable energy has come to fill the gap; and hence can completely become alternative energy resources for the conventional energy resources. Renewable energy is important because of the benefits it provides. The key benefits which are that renewable energy technologies are clean sources of energy that have a much lower environmental impact than conventional energy technologies.

b) Problem Statement

Despite the policy frame work for electricity production with renewable energy in Nigeria, the use of energy has still been majored on the generation from the cheap but environmental unfriendly energy resources-oil and gas. For electrical energy production, the use of centralized power plant is not encouraging due certain reliability factors such as vandalization of gas pipeline and power lines, voltage drop due to overload, frequent faults due to aging equipment and so and so forth. This factors has contributed in reducing energy production.

Most Nigerian based industries in an effort to help themselves and their businesses relied on diesel generator for electricity supply. A study by Tyler's (2002) *showed that of ''232 Nigerian based firms, 97% owned private generators and operated them for 67% of their production time''* (Tyler's, 2002). This cannot be economical, considering the operational cost associated with diesel generator, such as increase in diesel price, lack of maintenance personnel, scarcity and transportation, coupled with environmental impact.

Using a more sustainable approach for electricity generation (such as renewable energy hybrid system), will not only be profitable to the industries but also increase national energy mix can production; and encourage in decarbonizing the environment. Again, development of mini grids or decentralized power plants with the use of viable renewable energy resources can encourage reliable and sustainable power production and supply.

c) Research Aim

The aim of this project is to perform optimization of hybrid Wind/Photovoltaic renewable energy system for telecommunication industries in Port Harcourt.

d) Objectives of the Research

The specific objectives are stated as follows:

1. To investigate renewable energy potentials in Nigeria
2. To study selected two renewable energy resources(Wind and Solar PV) for power generation
3. To perform a design and load profile construction of the two selected renewable energy resources
4. To perform a comparative analysis of the selected energy schemes with a fossil generation system in terms of energy production, cost, based on Net-Present-Value(NPV)
5. To perform a sensitivity analysis of the optimized hybrid system

e) Significant of the Research

Renewable energy technologies are increasingly used to address energy shortages and to expand the range of services in both rural and urban areas.

Electrical energy has been seen as one important source of energy due to its higher transmissible power, its ability to readily transform to other forms of energy and the human capability to facilitate its storage. Electricity plays vital roles in our daily lives such as in cooking our food, hitting our water, powering our personal computer and many more. Energy is a very important catalyst for economic development of any country. Despite the importance of energy to socio-economic development, Nigeria has not being able to generate the maximum required amount of energy it needs for her population. It is important that the viability of this clean and sustainable resources be studied so that Nigeria can take advantage of global partnerships in the development of framework to support the technology.

f) Scope of the Research

There are so many renewable energy resources in Nigeria. But the project shall be limited to analysis of technical and economic impact of hybrid Wind/solar PV energy resources in Nigeria. The research location shall be SOUTH-SOUTH REIGION. The research shall not discuss grid connected renewable energy sources, where the use of power electronic such as STACOM device for the control of power is involved. And the research shall not develop a physical system.

II. Literature Review

a) Introduction

Nigeria is rich with both conventional and non-conventional energy resources as illustrated in table 3.1.

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Table 3.1: Energy Sources in Nigeria

Energy Resources In Nigeria	
Energy type	Reserve estimates
Crude oil	36 billion barrels
Natural gas	185 trillion cubic feet
Coal	2.75 billion metric tons
Hydro	14.7.0MW
Solar Radiation	3.5-7.0 KWh/m^2/day
Wind energy	2.0 – 4.0
Biomass	144 million tons/year
Waves and tidal energy	150,000 $TJ/16.6\times10^6\ ton/yr$

Source: Energy commission of Nigeria (ECN)

Source of electric power was first known in Nigeria in 1896 when a 30 KW, 50 Hz, single phase locomotive generator was installed in Ijora, Lagos, the then seat of British colony. In 1924, with the increasing population, a three phase, 50 Hz system of power system became known and electric power were been distributed in few cities of the country by some isolated generating stations like Cameroon's Development Corporation (CDC), African Timber and Plywood Company (ATPC) and Nigeria Electrical Supply Corporation (NESCO), In 1952, Electricity Corporation of Nigeria (ECN) was established and this gave birth to the Ijora Power Station which had 10 MW coal-fired turbo-generators, (Atandare, 2007).

Coal and hydropower and has been the source the nation's energy until when the activities of oil exploration started in 1950s.

Due to the environmental risk in the use of oil and gas and other forms of fossil generations, attention has been shifted globally to the use of renewable generations. Apart from attack on the environment, hike in oil price and security is another factor.

b) Review of Wind and Solar Potentials in Nigeria

Wind Energy Wind is a natural phenomenon related to the movement of air masses caused primarily by the differential solar heating of the earth's surface. Sambo (2005) State that seasonal variations in the energy received from the sun affects the strength and direction of the wind. The ease with which aero turbines transform energy in moving air to rotary mechanical energy suggests the use of electrical devices to convert wind energy to electricity. Wind energy has also been utilized, for decades, for water pumping as well as for the milling of grains.

Globally, Nigeria is located within low to moderate wind. Ojosu and Salawu (1989) carried out the most comprehensive nationwide study on wind energy availability and potential in Nigeria. The study uses Data on Wind speeds and directions for 22 meteorlogical Stations from the Nigerian Meteorological office, Oshodi near Lagos. The meteorological data are based on the 3-hourly records of wind for periods ranging from 12 to 33 years (1951 – 1983)

Other studies on the wind energy potentials for a number of Nigerian cities shows that the annual wind speed ranges from 2.32 m/s for Port Harcourt to a figure of 3.89 m/s for Sokoto. The maximum extractable power per unit area, for the same two sites was estimated at 4.51 and 21.97 watts per square metre of blade area, respectively. And when the duration of wind speeds greater than 3 m/s is considered than the energy per unit area works out as 168.63 and 1,556.35 kWh per square metre of blade area, again for Port Harcourt and Sokoto. (Sambo, 1987)

Ojosu and Salawu estimated the maximum energy obtainable from a 25m diameter wind turbine with an efficiency of 30% at 25m height to be about 97 MWhyear-for Sokoto, a site in the high wind speed regions, 50 MWh year- for Kano, 25.7 MWh year-1 for Lagos and 24.5 MWh year-1 from Port Harcourt. Table 2.2 shows the wind energy densities for other sites. (Ojosu and Salawu, 1990).

Table 2.1: Wind energy Density Estimates at 25 metre Height (Ojosu and Salawu, 1990)

Station	Mean wind speed at 25m Level (ms)	Monthly mean Wind Energy KWh/yr.	Annual Wind Energy KWh-2 year	Annual Wind energy from a wind Energy turbine in KWh year -1	
				Dia = 10m	Dia = 25m
Benin City	2.135	2.32	27.86	2,187.81	13,673.78
Calabar	1.702	1.12	13.42	1,053.69	6,587.53
Enugu	3.372	7.83	93.91	7,375.75	46,097.96
Ibadan	2.620	4.15	49.78	3,.909.79	24,436.19
Ilorin	2.078	1.23	14.73	1,157.06	7,230.57
Jos	4.430	16.05	192.64	15,129.60	94,559.98
Kaduna	3.605	9.91	188.88	9,36.81	58,355.08
Kano	3.516	8.57	102.86	8,078.61	50,491.28
Lagos	2.671	4.36	52.32	4,099.78	25,682.52
(Ikeja)					
Lokoja	2.235	2.60	31.21	,451.23	15,320.17
Maiduguri	3.486	8.42	101.01	7,933.61	49,583.17
Minna	1.589	1.05	12.60	989.60	6,185.01
Makurdi	2.689	4.44	53.27	4,183.51	26,148.85
Nguru	4.259	14.48	173.74	13,645.19	85,284.42
Oshogb	1.625	1.07	12.81	1,006.60	6,288.09
P.H.	2.640	4.17	49.98	3,925.48	24,533.88
Potiskum	3.636	9.44	113.25	8,894.35	55,591.46
Sokoto	4.476	16.47	197.68	15,525.75	97,035.94
Warri	2.027	2.02	24.20	1,.900.66	11,879.15
Yelwa	3.360	7.76	93.13	7,314.88	45,714.59
Yola	1.824	1.45	17.34	1,361.88	8,511.75
Zaria	2.891	5.32	63.88	5,017,26	31,357.02

Although use of wind energy for water supply has been known and used for hundreds of years, in recent times efforts have been directed largely towards the use of wind power for the generation of electricity and in the past twenty years or so rapid changes in technology have occurred and major wind powered generating plants have been installed, especially in the rural areas of the developed countries.

According to Bala*et al* (2000), Nigeria is endowed with an annual Average daily sunshine of 6.25 hours, ranging between about 3.5 hours at the coastal areas and 9.0 hours at the far northern boundary. Similarly, it has an annual average daily solar radiation of about 5.25 KW/m^2/day, varying between about 3.5 kWm^2/day at the coastal Area and 7.0kW/m2/day at the northern boundary. Nigeria receives about 4.851x 10^{12} KWh of energy per day from the sun. This is equivalent to about 1.082 million tones of oil Equivalent (mtoe) per day, and is about 4 thousand times the current daily crude oil reduction, and about 13 thousand times that of natural gas daily production based on energy unit. This huge energy resource from the sun is available for about 26% only of the day. The country is also characterized with some cold and dusty atmosphere during the harmattan, in its northern part, for a period of about four months (November-February) annually. (Bala*et al,* 2000).

Based on the land area of 924 x 10^3 km^2 for the country and an average of 5.535 kWh/m^2/day, Nigeria has an average of 1.804 x 10^{15} kWh of incident solar energy annually. This annual solar energy insolation value is about 27 times the nation total conventional energy resources in energy units and is over 117,000 times the amount of electric power generated in the county in 1998 (Chendo, 2002). In other words, about 3.7% only of the national land area is needed to be utilized in order to annual collect from the sun an amount of energy equal to the nation's conventional energy reserve.

Similarly, Okafor and Uzuegbu (2018) indicates that Nigeria is endowed with an annual Average daily sunshine of 6.25 hours, ranging between about 3.5 hours at the coastal areas and 9.0 hours at the far northern boundary. Similarly, it has an annual average daily solar radiation of about 5.25 KW/m^2/day, varying between about 3.5 kWm^2/day at the coastal Area and 7.0kW/m^2/day at the northern boundary. Nigeria receives about 4.851x 1012 KWh of energy per day from the sun. This is equivalent to about 1.082 million tons of oil Equivalent (mtoe) per day, and is about 4 thousand times the current daily crude oil reduction, and about 13 thousand times that of natural gas daily production based on energy unit. This huge energy resource from the sun is available for about 26% only of the day.

c) Review of Releted Works on Hybrid Wind-Solar PV System

Obuah and Alalibo (2017) performed a comparative analysis of Hybrid Photovoltaic/Diesel Energy System for Oil and Gas Industries in Nigeria. Their studies was based on a system that has low investment cost for the project life cycle of 25 years. The result of their studies shows that the cost of PV components with battery storage device was relatively high, but the system constituted a significant advantage when incorporated with diesel generation. Their research was commendable and educating as the approach for load sizing was thoughtful. However, their studies did not carry out sensitivity analysis of the hybrid system.

In 2014, Afrouzi*et al,* (2014) researched on the viability of renewable energy resources for hybrid of hydro, solar and wind. Their studies was based on a supposed remote residential area consisted of a total of 30 consumers, where each consumer needed loads of 2kW peak making a total or maximum of 60kW peak demand. Using HOMER for the studies, a PV/Wind/-Diesel Hybrid Energy System with was optimized based on system components with cheapest cost. However, their studies show that HOMER Diesel Hybrid Energy System with HOMER was the most economical one.

Similarly, Hassan *et al* (2016)made a research on Optimization of P/Wind/Diesel Hybrid Power System in HOMER for Rural Electrification of Muqdadiyah a rural region of Diyala State of Iraq. The research considered two renewable resources, namely, solar photovoltaic (PV) and wind turbine (WT), using a computer simulation and optimization of hybrid power generation system, HOMER. Their results show that it's not economically viable for a wind turbine to generate the electricity. But then a hybrid system comprising of PV and Diesel provided the solution to electrify the selected area resulted in a least- cost combination of the hybrid power system at a cost of about ($0.321/kWh).

III. Materials and Methods

a) Materials

The section of this work will take into details the materials needed in actualizing this study; Load Profile Datasheet, Metrological Datasheet, HOMER Pro Software and the simulation network

i. *Homer*

HOMER is a computer-based program provided by NREL which can give assistance in the tasks to configure, simulate, evaluate and optimize several choices of designs of various systems for distributed electricity generation and consumption units. HOMER allows for a basic comparative analysis of several alternatives for electrification, and estimates impacts of changes in loading parameters, impact on the environmental and potential emission of greenhouse gases.

Below are presented the task of the HOMER software needed for this study:

- Simulation of the system operation (energy balance for each of the 8760 hours of the year) comparing the energy demand and the capacity of the system to supply the energy on that hour, deciding for every hour how the generators operate and the loads of discharges of the batteries;
- Calculation of the energy balance for each proposed system that we want to consider, after the configuration is deemed feasible; and
- Estimating the costs of investment, equipment replacement, fuel, maintenance and operation.
- The final goal is basically to identify the lowest cost system capable of meeting the electricity demand of a particular consumer unit, urban or rural residence, community, company or industry.

b) Network Block Diagram

The figure below represents the block diagram for the network to be simulated

i. *Facility Network Diagram*

The block diagram below represents the proposed network of having the Gen on the AC Bus while the PV and battery bank on the DC bus, the converter converts the DC power to AC for the load and the AC to DC from the Gen to charge the battery when the needs arises.

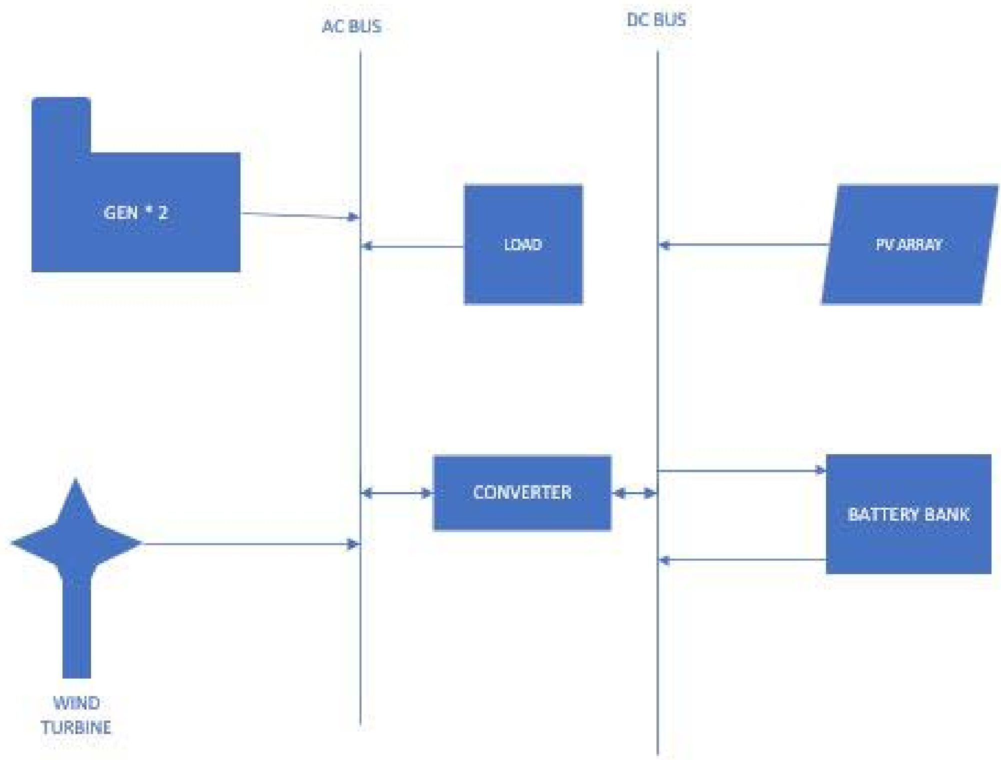


Figure 3.1: Block diagram

ii. *Facility Simulation Parameters*

The facility parameters to be used for simulation are shown on the table below.

Table 3.1: Simulation Parameter

S/N		
1	SITE ID	B1602
2	Co-ordinate	7.16938 9.28465
3	IHS ID	HIS_CRR_0751E
4	REGION	PHC
5	STATE	CROSS RIVER
6	VENDOR	HUAWEI
8	TENANTS	9 MOBILE
9	DG 1	20KVA
10	DG 2	20KVA
11	PEAK CURRENT	63 A
12	PEAK POWER	14490

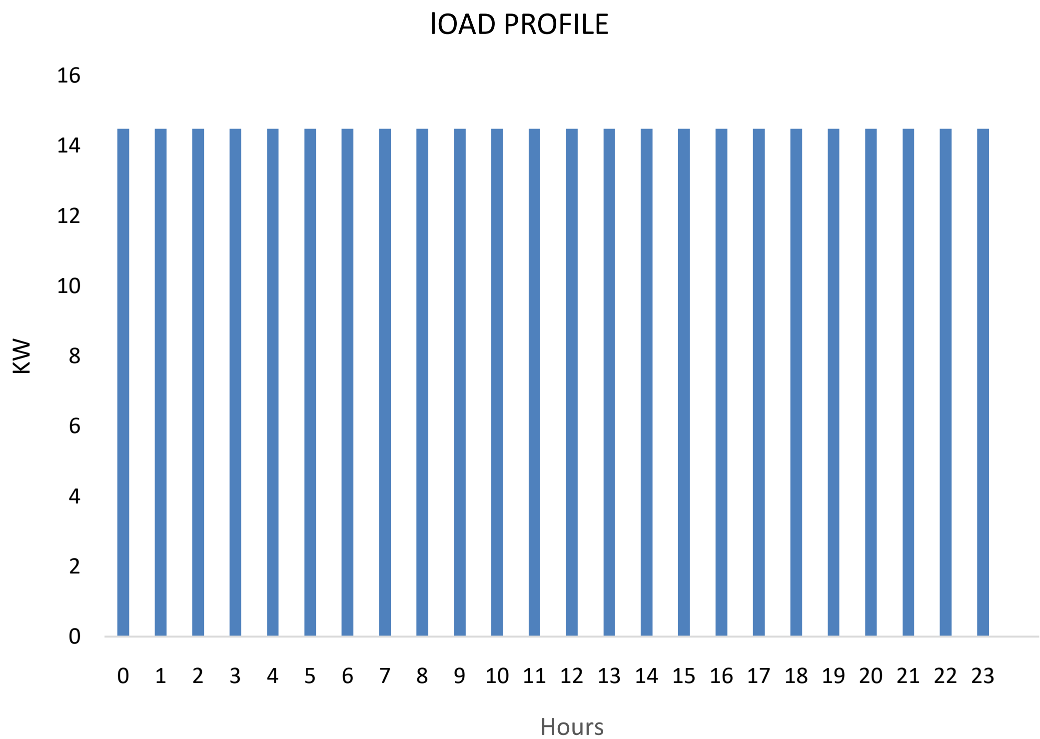


Figure 3.6: Load profile (source NASA 2020)

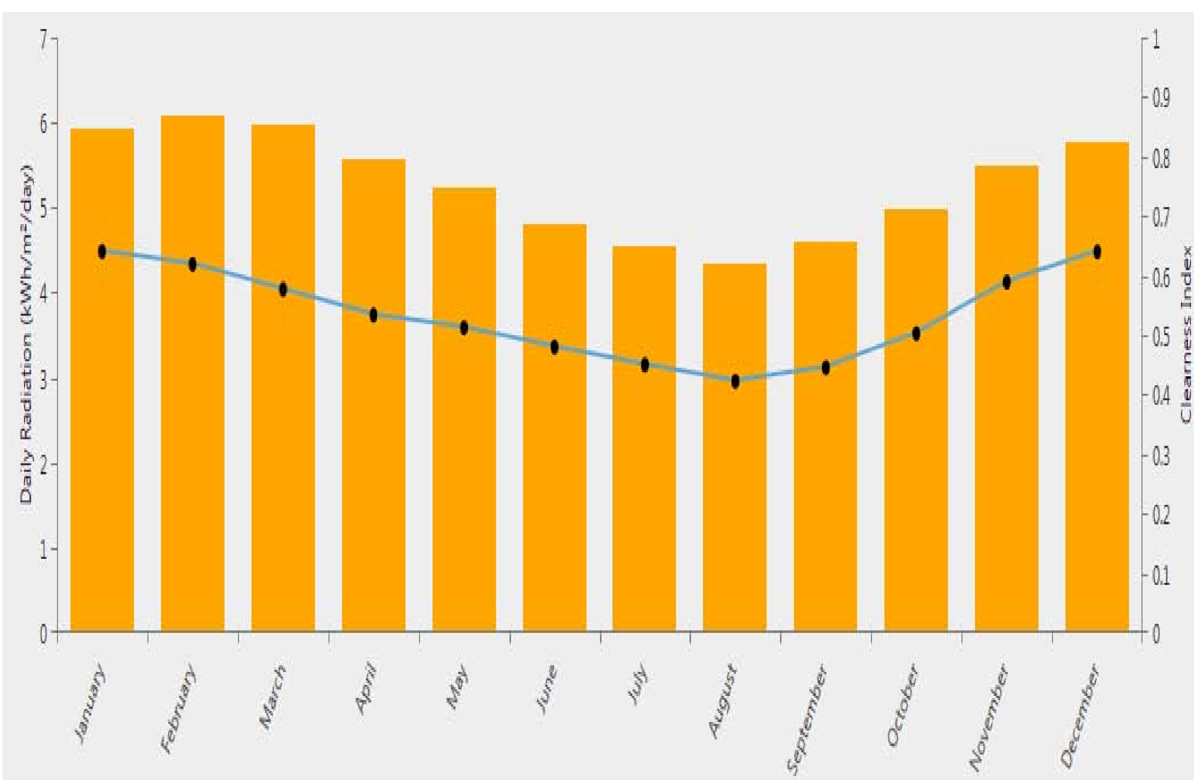


Figure 3.7: Solar Resources (Source: NASA 2020)

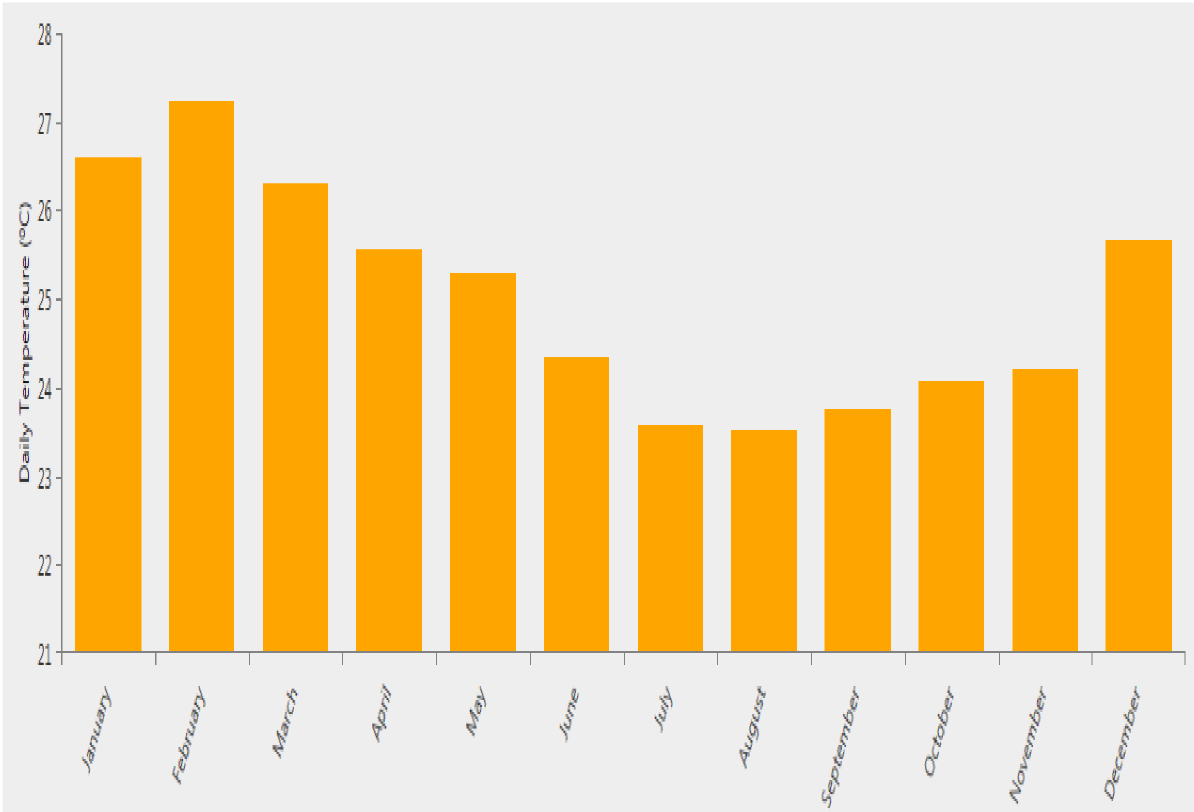


Figure 3.8: Temperature Resource (Source: NASA 2020)

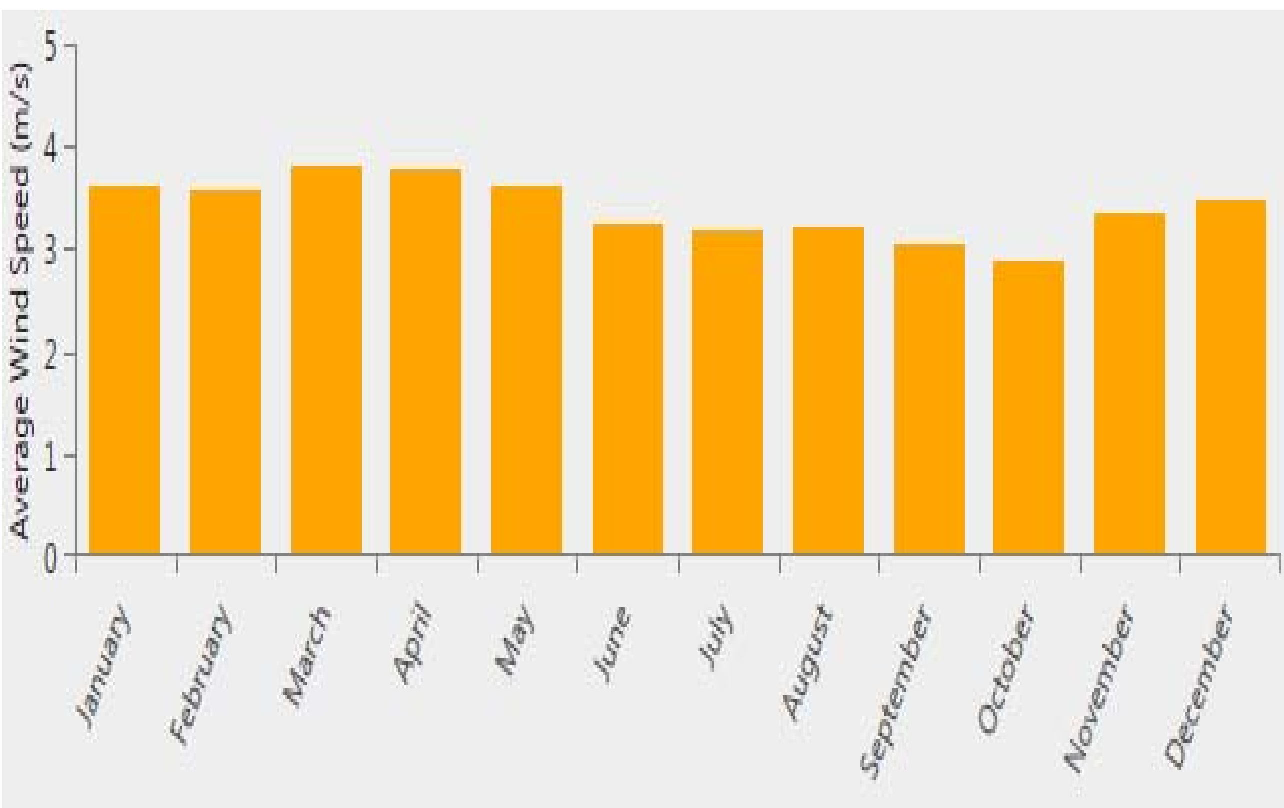


Figure 3.9: Solar speed (Source: NASA 2020)

HOMER Model Equations

iii. *PV array Output*

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) \left[1 + \alpha_P \left(T_c - T_{c,STC}\right)\right] \quad (3.1)$$

Where:

Y_{PV} = PV array rated capacity
f_{PV} = De-rating factor [%] of the PV
$\bar{G}_T$ = Incident solar radiation on the PV [kW/m^2]
$\bar{G}_{T,STC}$ = Incident radiation at standard test conditions [1 kW/m^2]
α_P =Temperature coefficient of power [%/°C]
T_c = PV cell temperature in the current time step [°C]
$T_{c,STC}$ = PV cell temperature under standard test conditions [25°C]
Source: HOMER Energy

Equation above is simplified thus below if temperature coefficient of power is assumed to be zero

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right) \quad (3.2)$$

Source: HOMER Energy

iv. *Maximum Battery Charge Power:*

This is used by HOMER to compute what amount of power that can absorb by the storage bank.

$$P_{batt,cmax,kbm} = \frac{kQ_1 e^{-K\Delta t} + Qkc\left(1 - e^{-K\Delta t}\right)}{1 - e^{-K\Delta t} + c\left(k\Delta t - 1 + e^{-K\Delta t}\right)} \quad (3.3)$$

Where:

Q_1 =Available amount of energy [kWh] in the storage at the beginning of the time step.
Q =Total amount of energy [kWh] in the storage at the beginning of the time step.
c =Storage capacity ratio [unit less].
k =Storage rate constant [h-1]
Δt =Length of the time step [h]
Source: HOMER Energy

v. *Maximum Amount of Power Discharge from Storage:*

The maximum amount of power that the storage bank can discharge over a specific length of time is given by the Kinetic Storage model equation:

$$P_{batt,dmax,kbm} = \frac{-kcQ_{max} + kQ_1 e^{-K\Delta t} + Qkc\left(1 - e^{-K\Delta t}\right)}{1 - e^{-K\Delta t} + c\left(k\Delta t - 1 + e^{-K\Delta t}\right)} \quad (3.4)$$

Where:

Q_1 =Amount of energy [kWh] available in the Storage Component at the beginning of the time step
Q = Total amount of energy [kWh] in the Storage Component at the beginning of the time step
Q_{max} = Total capacity [kWh] of the storage bank
c = Storage capacity ratio [unit less]
k = Storage rate constant [h-1]
Δt = Length of the time step [h]

IV. Results and Discussion

a) *Basic Simulation Terms*

i. *Net Present Cost (NPC)*

(The net present cost) or (Life-cycle cost) of a Component is the present value of all the costs of installing and operating the Component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. HOMER calculates the net present cost of each Component in the system, and of the system as a whole.

ii. *Cycle Changing Dispatch Strategy*

The generator is always operated at its rated capacity when in operation and the excess energy is used to charge the batteries.

iii. *Salvage Value*

Salvage value is the value remaining in a component of the power system at the end of the project lifetime.

iv. *Annualized Cost*

The annualized cost of a component is the cost that, if it were to occur equally in every year of the project lifetime, would give the same net present cost as the actual cash flow sequence associated with that component.

v. *Levelized Cost of Energy (COE)*

Level zed cost of energy (COE) as the average cost per kWh of useful electrical energy produced by the system.

b) *Presentation of Data*

The tables below show the Homer input Data and the optimization values

Table 4.0: Diesel Generator Data

S/N	Diesel Generator (GEN)	Sample Rate
1	Manufacturer	Homer Generic
2	Capacity	16KW
3	Capital	N2700,000.00
4	Replacement	N2700,000.00
5	Electric Bus	AC
6	Fuel Diesel	N224/L

Source: Authors Research

Table 4.1: Wind Turbine

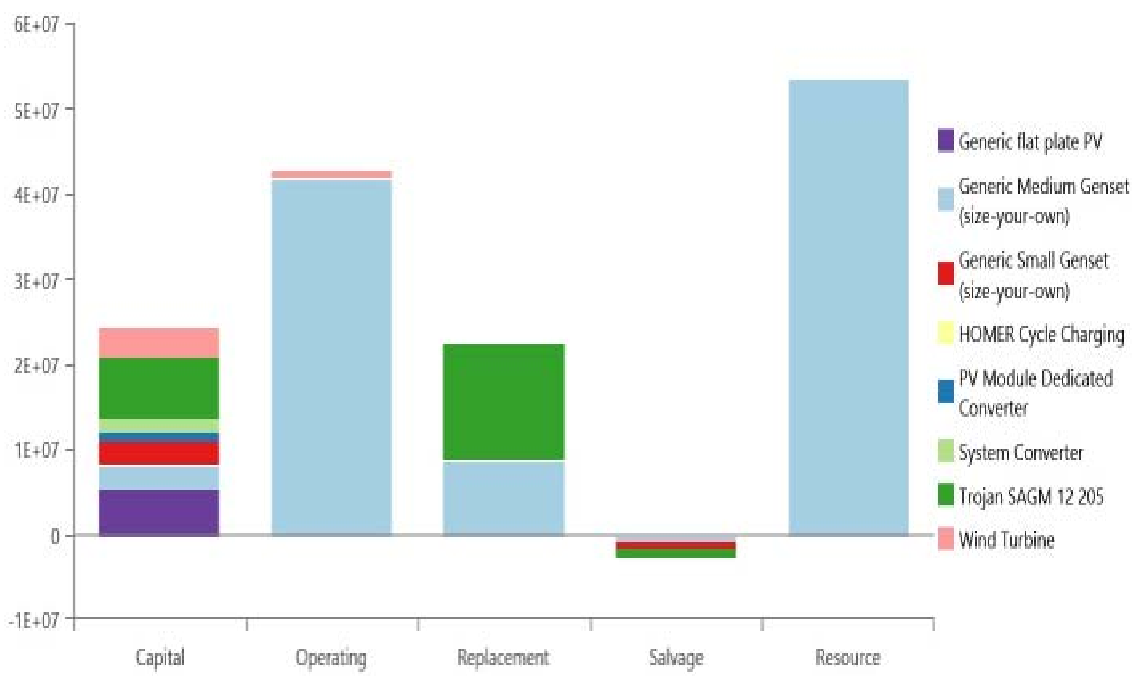
S/N	Generic flat PV	Sample Rate
1	Manufacturer	Homer Generic
2	Capacity	1 KW
3	Capital	N352,500.00
4	Replacement	N352,500.00
5	Electric Bus	DC
6	Capacity Optimization	0KW
		10KW
		20KW
		30KW

Table 4.7: System Architecture

Component	Name	Size	Unit
Generator #1	Generic Medium Genset (size-your-own)	16.0	kW
Generator #2	Generic Small Genset (size-your-own)	16.0	kW
PV	Generic flat plate PV	30.0	kW
Storage	Trojan SAGM 12 205	15	strings
Wind turbine	Wind Turbine	10	ea.
System converter	System Converter	20.0	kW
Dispatch strategy	HOMER Cycle Charging		

Source: Authors Research

The system architecture for the design is summarized on the above table. The size of the two 2 generators are16KW, the PV module is 30KW, the battery storage for the system is of 15 strings, the system converter is rated at 20KWwhile the wind turbine is of 10. and it also uses cycle changing dispatch strategy



Graph 4.0: System architecture

The above graph shows the system cost summary

Table 4.8: Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic flat plate PV	₦5.40M	₦0.00	₦0.00	₦0.00	₦0.00	₦5.40M
Generic Medium Genset (size-your-own)	₦2.70M	₦41.8M	₦8.69M	-₦524,657	₦53.6M	₦106M
Generic Small Genset (size-your-own)	₦2.70M	₦0.00	₦0.00	-₦1.13M	₦0.00	₦1.57M
HOMER Cycle Charging	₦5,000	₦0.00	₦0.00	₦0.00	₦0.00	₦5,000
PV Module Dedicated Converter	₦1.08M	₦0.00	₦0.00	₦0.00	₦0.00	₦1.08M
System Converter	₦1.60M	₦0.00	₦0.00	₦0.00	₦0.00	₦1.60M
Trojan SAGM 12 205	₦7.20M	₦0.00	₦13.7M	-₦1.11M	₦0.00	₦19.8M
Wind Turbine	₦3.53M	₦978,734	₦0.00	₦0.00	₦0.00	₦4.50M
System	₦24.2M	₦42.7M	₦22.4M	-₦2.76M	₦53.6M	₦140M

The NPC for 15yrs period is ₦140M that is ₦ (5.40M + 106M + 1.57M + 5000 + 1.08M + 1.60 M + 19.8M + 4.50M).

Table 4.9: Annualized Costs

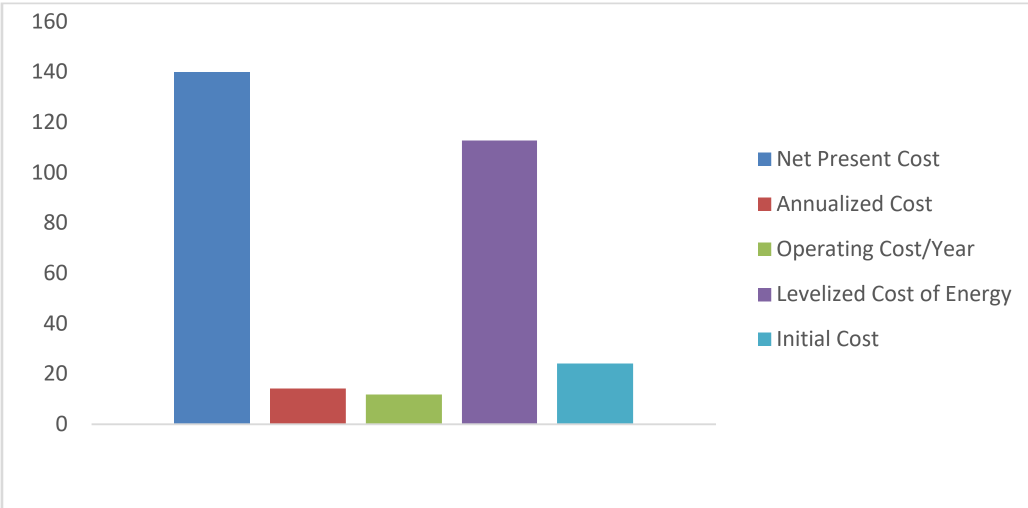
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic flat plate PV	₦551,733	₦0.00	₦0.00	₦0.00	₦0.00	₦551,733
Generic Medium Genset (size-your-own)	₦275,866	₦4.27M	₦888,069	-₦53,606	₦5.47M	₦10.9M
Generic Small Genset (size-your-own)	₦275,866	₦0.00	₦0.00	-₦115,287	₦0.00	₦160,579
HOMER Cycle Charging	₦510.86	₦0.00	₦0.00	₦0.00	₦0.00	₦510.86
PV Module Dedicated Converter	₦110,347	₦0.00	₦0.00	₦0.00	₦0.00	₦110,347
System Converter	₦163,476	₦0.00	₦0.00	₦0.00	₦0.00	₦163,476
Trojan SAGM 12 205	₦735,644	₦0.00	₦1.40M	-₦113,117	₦0.00	₦2.03M
Wind Turbine	₦360,159	₦100,000	₦0.00	₦0.00	₦0.00	₦460,159
System	₦2.47M	₦4.37M	₦2.29M	-₦282,010	₦5.47M	₦14.3M

The annualised cost of the grid system is ₦143.M

Other results generated by the HOMER software on grid but not related to cost are attached in appendix A *c) Discussion of Findings*

Table 4.10: Optimization Table

S/N	OPTIMIZATION	GRID SYSTEM COST
1	Net Present Cost	₦140 million
2	Annualized Cost	₦14.3 million
3	Operating Cost/Year	₦11.8 million
4	Levelized Cost of Energy	₦112.83
5	Initial Cost	₦24.2 million



Graph 4.1

The above table and graph show the configuration hybrid configuration of the above system for a period of 15years life time with a dispatch strategy of “Cycle Charging”.

15 year operational cost analysis

₦11,800,000 x 15years = ₦177000000

Adding the operational cost to the initial setup cost of ₦24,200,000

₦177000000 + ₦24,200,000 = ₦201,200,000

V. Summary, Conclusion and Recommendations

a) Summary

This study examined the comparative cost analysis for improving power supply through off-grid solar energy utilization in Nigeria.

Chapter 1 introduce the importance of power supply as it cuts across all aspect of life ranging from residential, commercial and industrial uses. It equally looks at its effect on living standard and the world economy

Chapter 2 was used to review different papers that discusses history/issues concerning Nigeria power supply and its framework. Nigeria solar energy potentials, site identification and the components needed to build a solar plant.

Chapter 3 discusses the method and material used in carrying the research. How the research data were obtained and how/which software was used to analyzed the data

Chapter 4 dealt with data presentation and the analysis of the data using HOMER Energy.

b) Conclusion

The comparative cost analysis shows that the following parameters:

- Net Present Cost (NPC)
- Annualized Cost
- levelized Cost of Energy (LCOE)
- Operating Cost/Year

Are lower or cheaper for the PV/Generator Network compared to Grid/Generator network. The only setback observed was the huge initial cost of setting up the PV system but at the long run it is still better when compared to usingjust grid or fusil.

The economic analysis demonstrated that government and other organization should invest in off-grid renewable (Solar) energy power plant to improve the standard of living and bring down the cost of doing business.

c) Recommendations

Based on this study, the followings are recommended

1. Domestication of mechanization of solar/wind energy components and equipment in the country and technology advancement should be encouraged by the government.

2. Government should introduce policies like interest free low loan or loan with minimal interest rate to encourage large organizations, institutions, estate, etc. to build their own power generating plant with the excess power generated sold to the grid.
3. Finally, renewable resources are enormous in Nigeria, identifying the best sources to be harness in different part of the country is key to increase power generation and sustain economic growth.

d) Contribution to Knowledge

This study has established that there is comparative cost advantage of solar energy utilization in improving power supply in Nigeria as well as helping in global worming by reducing use of fuel which constantly deplete the ozone layer most especially if the right policies are introduced by government.

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e) Resources and techniques with sufficient complete experimental details (wherever possible by reference) to permit repetition, sources of information must be given, and numerical methods must be specified by reference.
f) Results which should be presented concisely by well-designed tables and figures.
g) Suitable statistical data should also be given.
h) All data must have been gathered with attention to numerical detail in the planning stage.

Design has been recognized to be essential to experiments for a considerable time, and the editor has decided that any paper that appears not to have adequate numerical treatments of the data will be returned unrefereed.

i) Discussion should cover implications and consequences and not just recapitulate the results; conclusions should also be summarized.
j) There should be brief acknowledgments.
k) There ought to be references in the conventional format. Global Journals recommends APA format.

Authors should carefully consider the preparation of papers to ensure that they communicate effectively. Papers are much more likely to be accepted if they are carefully designed and laid out, contain few or no errors, are summarizing, and follow instructions. They will also be published with much fewer delays than those that require much technical and editorial correction.

The Editorial Board reserves the right to make literary corrections and suggestions to improve brevity.

Format Structure

It is necessary that authors take care in submitting a manuscript that is written in simple language and adheres to published guidelines.

All manuscripts submitted to Global Journals should include:

Title

The title page must carry an informative title that reflects the content, a running title (less than 45 characters together with spaces), names of the authors and co-authors, and the place(s) where the work was carried out.

Author details

The full postal address of any related author(s) must be specified.

Abstract

The abstract is the foundation of the research paper. It should be clear and concise and must contain the objective of the paper and inferences drawn. It is advised to not include big mathematical equations or complicated jargon.

Many researchers searching for information online will use search engines such as Google, Yahoo or others. By optimizing your paper for search engines, you will amplify the chance of someone finding it. In turn, this will make it more likely to be viewed and cited in further works. Global Journals has compiled these guidelines to facilitate you to maximize the web-friendliness of the most public part of your paper.

Keywords

A major lynchpin of research work for the writing of research papers is the keyword search, which one will employ to find both library and internet resources. Up to eleven keywords or very brief phrases have to be given to help data retrieval, mining, and indexing.

One must be persistent and creative in using keywords. An effective keyword search requires a strategy: planning of a list of possible keywords and phrases to try.

Choice of the main keywords is the first tool of writing a research paper. Research paper writing is an art. Keyword search should be as strategic as possible.

One should start brainstorming lists of potential keywords before even beginning searching. Think about the most important concepts related to research work. Ask, "What words would a source have to include to be truly valuable in a research paper?" Then consider synonyms for the important words.

It may take the discovery of only one important paper to steer in the right keyword direction because, in most databases, the keywords under which a research paper is abstracted are listed with the paper.

Numerical Methods

Numerical methods used should be transparent and, where appropriate, supported by references.

Abbreviations

Authors must list all the abbreviations used in the paper at the end of the paper or in a separate table before using them.

Formulas and equations

Authors are advised to submit any mathematical equation using either MathJax, KaTeX, or LaTeX, or in a very high-quality image.

Tables, Figures, and Figure Legends

Tables: Tables should be cautiously designed, uncrowned, and include only essential data. Each must have an Arabic number, e.g., Table 4, a self-explanatory caption, and be on a separate sheet. Authors must submit tables in an editable format and not as images. References to these tables (if any) must be mentioned accurately.

Figures

Figures are supposed to be submitted as separate files. Always include a citation in the text for each figure using Arabic numbers, e.g., Fig. 4. Artwork must be submitted online in vector electronic form or by emailing it.

Preparation of Eletronic Figures for Publication

Although low-quality images are sufficient for review purposes, print publication requires high-quality images to prevent the final product being blurred or fuzzy. Submit (possibly by e-mail) EPS (line art) or TIFF (halftone/ photographs) files only. MS PowerPoint and Word Graphics are unsuitable for printed pictures. Avoid using pixel-oriented software. Scans (TIFF only) should have a resolution of at least 350 dpi (halftone) or 700 to 1100 dpi (line drawings). Please give the data for figures in black and white or submit a Color Work Agreement form. EPS files must be saved with fonts embedded (and with a TIFF preview, if possible).

For scanned images, the scanning resolution at final image size ought to be as follows to ensure good reproduction: line art: >650 dpi; halftones (including gel photographs): >350 dpi; figures containing both halftone and line images: >650 dpi.

Color charges: Authors are advised to pay the full cost for the reproduction of their color artwork. Hence, please note that if there is color artwork in your manuscript when it is accepted for publication, we would require you to complete and return a Color Work Agreement form before your paper can be published. Also, you can email your editor to remove the color fee after acceptance of the paper.

Tips for Writing a Good Quality Engineering Research Paper

Techniques for writing a good quality engineering research paper:

1. Choosing the topic: In most cases, the topic is selected by the interests of the author, but it can also be suggested by the guides. You can have several topics, and then judge which you are most comfortable with. This may be done by asking several questions of yourself, like "Will I be able to carry out a search in this area? Will I find all necessary resources to accomplish the search? Will I be able to find all information in this field area?" If the answer to this type of question is "yes," then you ought to choose that topic. In most cases, you may have to conduct surveys and visit several places. Also, you might have to do a lot of work to find all the rises and falls of the various data on that subject. Sometimes, detailed information plays a vital role, instead of short information. Evaluators are human: The first thing to remember is that evaluators are also human beings. They are not only meant for rejecting a paper. They are here to evaluate your paper. So present your best aspect.

2. Think like evaluators: If you are in confusion or getting demotivated because your paper may not be accepted by the evaluators, then think, and try to evaluate your paper like an evaluator. Try to understand what an evaluator wants in your research paper, and you will automatically have your answer. Make blueprints of paper: The outline is the plan or framework that will help you to arrange your thoughts. It will make your paper logical. But remember that all points of your outline must be related to the topic you have chosen.

3. Ask your guides: If you are having any difficulty with your research, then do not hesitate to share your difficulty with your guide (if you have one). They will surely help you out and resolve your doubts. If you can't clarify what exactly you require for your work, then ask your supervisor to help you with an alternative. He or she might also provide you with a list of essential readings.

4. Use of computer is recommended: As you are doing research in the field of research engineering then this point is quite obvious. Use right software: Always use good quality software packages. If you are not capable of judging good software, then you can lose the quality of your paper unknowingly. There are various programs available to help you which you can get through the internet.

5. Use the internet for help: An excellent start for your paper is using Google. It is a wondrous search engine, where you can have your doubts resolved. You may also read some answers for the frequent question of how to write your research paper or find a model research paper. You can download books from the internet. If you have all the required books, place importance on reading, selecting, and analyzing the specified information. Then sketch out your research paper. Use big pictures: You may use encyclopedias like Wikipedia to get pictures with the best resolution. At Global Journals, you should strictly follow here.

6. Bookmarks are useful: When you read any book or magazine, you generally use bookmarks, right? It is a good habit which helps to not lose your continuity. You should always use bookmarks while searching on the internet also, which will make your search easier.

7. Revise what you wrote: When you write anything, always read it, summarize it, and then finalize it.

8. Make every effort: Make every effort to mention what you are going to write in your paper. That means always have a good start. Try to mention everything in the introduction—what is the need for a particular research paper. Polish your work with good writing skills and always give an evaluator what he wants. Make backups: When you are going to do any important thing like making a research paper, you should always have backup copies of it either on your computer or on paper. This protects you from losing any portion of your important data.

9. Produce good diagrams of your own: Always try to include good charts or diagrams in your paper to improve quality. Using several unnecessary diagrams will degrade the quality of your paper by creating a hodgepodge. So always try to include diagrams which were made by you to improve the readability of your paper. Use of direct quotes: When you do research relevant to literature, history, or current affairs, then use of quotes becomes essential, but if the study is relevant to science, use of quotes is not preferable.

10. Use proper verb tense: Use proper verb tenses in your paper. Use past tense to present those events that have happened. Use present tense to indicate events that are going on. Use future tense to indicate events that will happen in the future. Use of wrong tenses will confuse the evaluator. Avoid sentences that are incomplete.

11. Pick a good study spot: Always try to pick a spot for your research which is quiet. Not every spot is good for studying.

12. Know what you know: Always try to know what you know by making objectives, otherwise you will be confused and unable to achieve your target.

13. Use good grammar: Always use good grammar and words that will have a positive impact on the evaluator; use of good vocabulary does not mean using tough words which the evaluator has to find in a dictionary. Do not fragment sentences. Eliminate one-word sentences. Do not ever use a big word when a smaller one would suffice.

Verbs have to be in agreement with their subjects. In a research paper, do not start sentences with conjunctions or finish them with prepositions. When writing formally, it is advisable to never split an infinitive because someone will (wrongly) complain. Avoid clichés like a disease. Always shun irritating alliteration. Use language which is simple and straightforward. Put together a neat summary.

14. Arrangement of information: Each section of the main body should start with an opening sentence, and there should be a changeover at the end of the section. Give only valid and powerful arguments for your topic. You may also maintain your arguments with records.

15. Never start at the last minute: Always allow enough time for research work. Leaving everything to the last minute will degrade your paper and spoil your work.

16. Multitasking in research is not good: Doing several things at the same time is a bad habit in the case of research activity. Research is an area where everything has a particular time slot. Divide your research work into parts, and do a particular part in a particular time slot.

17. Never copy others' work: Never copy others' work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. Go to seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. Think technically: Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

21. Adding unnecessary information: Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn't be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.

22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.

23. Upon conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

The introduction: This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

The discussion section:

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to prior workings.

Writing a research paper is not an easy job, no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record-keeping are the only means to make straightforward progression.

General style:

Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

To make a paper clear: Adhere to recommended page limits.

Mistakes to avoid:

- Insertion of a title at the foot of a page with subsequent text on the next page.
- Separating a table, chart, or figure—confine each to a single page.
- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.

- Use paragraphs to split each significant point (excluding the abstract).
- Align the primary line of each section.
- Present your points in sound order.
- Use present tense to report well-accepted matters.
- Use past tense to describe specific results.
- Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
- Avoid use of extra pictures—include only those figures essential to presenting results.

Title page:

Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite references at this point.

An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

- Fundamental goal.
- To-the-point depiction of the research.
- Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- Single section and succinct.
- An outline of the job done is always written in past tense.
- Concentrate on shortening results—limit background information to a verdict or two.
- Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- Explain the value (significance) of the study.
- Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- Briefly explain the study's tentative purpose and how it meets the declared objectives.

Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

- Report the method and not the particulars of each process that engaged the same methodology.
- Describe the method entirely.
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
- Simplify—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings—save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:

- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.

- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

The Administration Rules

Administration Rules to Be Strictly Followed before Submitting Your Research Paper to Global Journals Inc.

Please read the following rules and regulations carefully before submitting your research paper to Global Journals Inc. to avoid rejection.

Segment draft and final research paper: You have to strictly follow the template of a research paper, failing which your paper may get rejected. You are expected to write each part of the paper wholly on your own. The peer reviewers need to identify your own perspective of the concepts in your own terms. Please do not extract straight from any other source, and do not rephrase someone else's analysis. Do not allow anyone else to proofread your manuscript.

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CRITERION FOR GRADING A RESEARCH PAPER (COMPILATION) BY GLOBAL JOURNALS

Please note that following table is only a Grading of "Paper Compilation" and not on "Performed/Stated Research" whose grading solely depends on Individual Assigned Peer Reviewer and Editorial Board Member. These can be available only on request and after decision of Paper. This report will be the property of Global Journals.

Topics	Grades		
	A-B	**C-D**	**E-F**
Abstract	Clear and concise with appropriate content, Correct format. 200 words or below	Unclear summary and no specific data, Incorrect form Above 200 words	No specific data with ambiguous information Above 250 words
Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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