Energy Production and Storage Optimal Sizing for Research Infrastructures: A Case Study at KARA Accelerator

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***Abstract*—Large research facilitates like particle accelerators have huge power consumption requirements leading to significant carbon footprint and high energy costs. In light of ongoing global effort to reduce energy related CO_2 emissions and rising energy costs, the Karlsruhe Research Accelerator (KARA) at KIT under Horizon Europe project Research Facility 2.0 will design and optimally size a local renewable based energy production system to ensure environmentally sustainable and economically viable energy generation for such facilities. The proposed energy production system, connected to public utility electric grid, constitutes of solar, wind and geothermal generators supported by battery energy storage. This study will provide a framework for sizing of a energy production system using a yearly KARA load profile such that optimal sizing is obtained as a result of single-objective optimization based on total system net present cost of the proposed system. Various different configurations of energy production system are compared and sizing results reveal that hybrid configuration where all the generators are integrated is the most cost effective. Moreover, the proposed methodology can also be adapted to other accelerator facilities, and the results can serve as a reference for the future design of accelerator facilities.**

***Index Terms*—Hybrid Renewable Energy Generators, energy production system, Sustainability, battery storage system, optimization, Particle Accelerator, Research Infrastructures**

I. Introduction

The breakthroughs in science depend on rigorous scientific effort and costly research infrastructures. The cost and scale of such infrastructures drastically increases as we move to basic research such as particle physics as evident by particle accelerator research infrastructures spread across the globe. The scale of particle accelerators directly correlates with higher collision energy requirements essential for breaking the existing barriers in physics research which translates into huge electrical power demand. For instance, the currently operational research particle accelerators are associated with huge electric power consumptions reaching up to 100 MW equivalent to large industrial units and whole communities. Moreover, this energy demand is projected to increase several times for future accelerators such as Compact Linear Collider (CLIC) and Future Circular Collider (FCC) [1] [2]. This continuously increasing scale of particle research accelerators, associated energy costs and time intensive basic research is giving rise to the questions by the society on need of such infrastructure in the first place which are funded by public money.

In order to increase the acceptance in society, the low cost and environmentally sustainable local energy generation is one of potential directions. This is because no compromises can be made on increasing scale of such facilities with unprecedented energy demands and time intensive nature of basic research as it would hinder the progress of science. Therefore, the research effort could be focused on technically viable alternative sources of energy [3]; however, ensuring cost effectiveness as well as environment sustainability tends to increases the complexity of problem. One possibility could be a hybrid energy production system integrating renewable energy generators (REG) coupled with electric utility grid for covering the energy demand. The objective could be to reduce the dependency on the electric grid ensuring environmental and financial sustainability. However, though the integration of REG introduces the possibility to achieve environmental sustainable energy generation, the intermittent nature of REG renders it difficult to ensure power supply stability and economical energy generation as it adversely affects the system stability by introducing voltage and frequency fluctuations [4].

The power supply stability, which not only hinders large scale integration of REG into energy production system but is also essential requirement for the particle accelerators, characterized by their strict power quality requirements and low power demand flexibility can be achieved by diversification of renewable energy sources along with the introduction of energy storage system (ESS) for enhanced stability [5]

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[6]. On the other hand, the low cost of energy generation can be ensured by proper design and accurate capacity optimization of energy production system while ensuring that no physical and optimization constraints are violated. In the literature, various methodologies are available which utilizes different approaches for optimally sizing the energy production system for diverse applications including residential houses, whole residential communities, commercial buildings, ships and industrial facilities. Detailed reviews on energy production system sizing problem can be found in [7] and [8].

However, in current study, the literature review is mainly focused on design of on-grid industrial energy production systems with REG. This is because as per author's knowledge, no studies are available on energy production system design for particle accelerators. Also, the particular selection of industrial energy production systems is because accelerators and large industrial facilities have equivalent levels of energy demand i.e. in units of several Hundred MWs. In the literature, many studies have discussed design and operational optimization of industrial energy production system and a detailed review can be found in [9]. For instance, a multi-objective optimization of hybrid energy on-grid microgird for industrial complex is carried out using metaheuristic optimization algorithms. The capacity of solar, wind, diesel generators and batteries is optimized for achieving minimum cost and CO_2 emission. The results reveal a trade-off between CO_2 emissions and system cost. Also, the study found that longer lifetime of energy production system results in larger integration of REG as part of optimal design [10]. Another similar study focused on optimizing a hybrid microgrid for total cost minimization of an industrial oil field. The proposed energy production system integrated cogeneration plant with REG including solar and wind supported by batteries. The results found the optimally sized energy production system cost nearly 193 million dollars and include a solar plant, two cogeneration plants, two wind generators, a battery storage system and a reversible AC/DC converter [11].

Recently, various other studies have also investigated the optimal design of energy production systems for different industrial applications including mining [12], textile [13], industrial park [14] and harbor area industries [15]. In these studies, energy production systems are proposed to satisfy the load demand ranging between 0.4-15 MW and the corresponding optimal costs for such systems vary between 11-81 million dollars. It is evident from the above discussion that industrial energy production systems are very costly to implement and depend on type of industrial application. Also, as stated previously, no proper framework is available in the literature focusing on optimal design of hybrid energy energy production systems for particle accelerators. Therefore, this study investigates the potential of integrating renewable energy energy production systems for Karlsruhe Research Accelerator (KARA). The specific contributions of this study are as follows:

- Proposed an optimization framework for the optimal sizing of a energy production system for KARA, which can be extended to other accelerator facilities.
- Compared various unique configurations of the proposed energy production system.

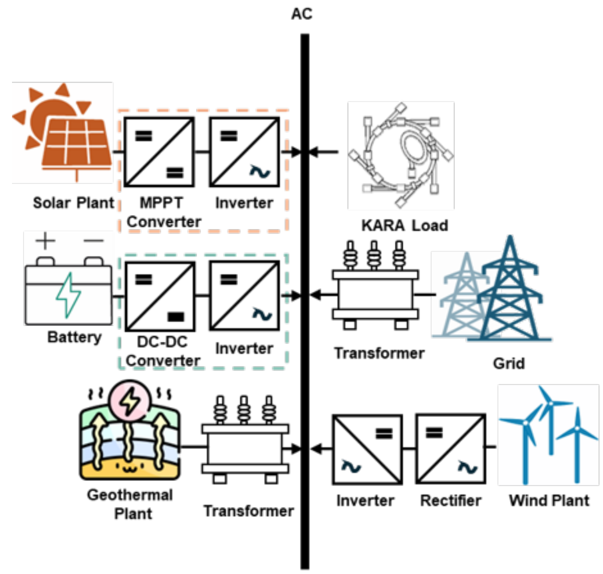

Fig. 1. Schematic of Proposed energy production system Configuration

II. Mathematical Model of Energy Production System

The energy production system proposed in this study consists of solar, wind and geothermal generators connected with battery storage, public electric grid, and accelerator load as shown in Fig. 1. Further details about selected mathematical models of energy production system components can be found in [16] and [17].

A. Solar Generator

The net electric power generated by an array of solar panels is modeled as given by (1):

$$P_{\text{PV}} = N_{\text{PV}} \cdot SR \cdot (\eta \cdot \eta_{\text{temp}} \cdot \eta_{\text{degradation}}) \cdot A_{\text{PV}}, \qquad (1)$$

The variable η_{temp} is given by:

$$\eta_{\text{temp}} = 1 - \alpha(T_c - T_{c,\text{STC}}) \qquad (2)$$

The cell temperature T_c is mathematically formulated as:

$$T_c = AT + \frac{SR \cdot (\text{NOCT} - 20)}{800} \qquad (3)$$

Where N_{PV} represents the number of solar panels, P_{PV} (kW) corresponds to the power generated from the solar array, solar radiation falling on arrays is given by SR (kW/m^2), A_{PV} (m^2) represents the surface area of the solar panel selected as $1.997\,\text{m}^2$, the solar panel efficiency is given by η, the loss in PV power due to higher cell temperature is given by η_{temp}, and the degradation factor is given by $\eta_{\text{degradation}}$, which is assumed to be $80\,\%$. T_c (°C) represents the PV cell temperature, α (%/°C) is the temperature coefficient set as -0.0031 %/°C, and

$T_{c,\text{STC}}$ is the cell temperature under standard test conditions (STC) fixed at 25 °C. AT (°C) is the ambient air temperature, and NOCT (°C) is the nominal operating cell temperature fixed at 46 °C.

B. Wind Power Generator

The net electric power generated by wind generators as a function of wind speed is mathematically modeled as given by (4):

$$P_{\text{WT}} = N_{\text{WT}} \cdot \begin{cases} RP_{\text{WT}} \cdot \frac{(WS^2 - WS_{\text{ci}}^2)}{(WS_{\text{r}}^2 - WS_{\text{co}}^2)}, & WS_{\text{ci}} \leq WS \leq WS_{\text{r}}, \\ RP_{\text{WT}}, & WS_{\text{r}} \leq WS \leq WS_{\text{co}}, \\ 0, & \text{Other cases.} \end{cases} \tag{4}$$

Where P_{WT} (kW) represents the total output power of a wind turbine, N_{WT} represents the number of wind turbines and WS (m/s) represents local wind speed. WS_{ci}, WS_{r} and WS_{co} represent the cut-in, rated, and cut-out wind speeds of the turbine, respectively, with values selected as 3 m/s, 11.6 m/s and 25 m/s. RP_{WT} (kW) represents the rated electrical power output of the specific wind turbine. Moreover, a wind speed correction is also implemented to consider the wind turbine height and height at which WS is actually measured.

$$WS = WS_{\text{ref}} \times \left(\frac{H_{\text{WT}}}{H_{\text{ref}}} \right)^{0.143}$$

In this formula, WS represents the wind speed at the wind turbine height H_{WT}, while WS_{ref} is the wind speed measured at the reference height H_{ref}. The reference height H_{ref} is 16 meters, which is the height at which the wind speed measurement is taken. The wind turbine height H_{WT} is considered to be 80 meters.

C. Geothermal Plant

The net electric power generated by geothermal modular generators is modeled by (5):

$$P_{\text{GTG}} = P_{\text{rated}}, \tag{5}$$

where P_{GTG} (kW) is the electrical power output of the geothermal generator and P_{rated} (kW) is the rated power of the selected geothermal generator after condescending all the loses.

D. Battery Storage

The operation of the Battery Storage System (BSS) is modeled as given by (6) and (7):

$$E_{\text{BSS}}(t) = \begin{cases} \left(E_{\text{TREG}}(t) - \frac{E_L(t)}{\eta_{\text{conv}}} \right) \cdot \eta_{\text{RT}}, & \text{Charging} \\ \frac{(E_L(t) - E_{\text{TREG}}(t) \cdot \eta_{\text{conv}})}{\eta_{\text{RT}}}, & \text{Discharging} \end{cases} \tag{6}$$

$$SOC_{\text{BSS}}(t) = SOC_{\text{BSS}}(t-1) \pm E_{\text{BSS}}(t), \tag{7}$$

E_{TREG} (kW) represents the total generation of renewable energy, which is the sum of solar, wind, and geothermal power generation. where the $\pm$ symbol indicates addition for charging and subtraction for discharging. E_{BESS} (kW) is the charging or discharging energy of the BESS, SOC_{batt} (kWh) is the state of charge of the BESS, and t is the time step, E_L(kW) is the load demand, η_{conv} and η_{RT} represent power converter efficiency and the round-trip efficiency of the BESS respectively.

E. Transformer

In this study, the required ratings of these devices is decided based on maximum power flow through the connected component and is determined by the model given by (8).

$$P_{\text{TR}} = \frac{\max(P_i)}{PF}, \tag{8}$$

where P_{TR} (kVA) represents the rated power of the transformer, and P_i (kW) is the power profile generated by the i-th component of the energy production system and lastly PF is the power factor which is assumed to be 0.8 for this study.

F. Power Converter

The rated capacity of power converter for each energy production system component is determined by the model given by (9). In this study, the optimal size of these devices is calculated based on maximum power flow through individual energy production system component.

$$P_{\text{PC}} = \max(P_i), \tag{9}$$

where P_{PC} (kW) represents the rated power of the power converter, and P_i (kW) is the power profile generated by the i-th component of the energy production system.

G. Electric Grid

The public electric grid is assumed as available all the time which can provide any deficit of load demand. The unit cost for purchasing electricity from the public grid is considered as 0.21 \$/kWh for a research facility. The value is assumed to lie in between residential tariffs (0.17 \$/kWh) and industrial tariffs (0.25 \$/kWh).

H. Financial Modeling

The mathematical formulation for cost modeling of energy production system is given by equation (10), where total net present cost (TNPC) over project lifetime is the sum of the initial investment cost (IIC), the operation cost (OMC), and the component replacement cost (CRC), and the electricity grid costs (GC):

$$\text{TNPC} = \text{IIC} + \text{OMC} + \text{CRC} + \text{GC} \tag{10}$$

$$\text{IIC} = N_r \cdot \text{IIC}_i \tag{11}$$

$$\text{OMC} = \text{OMC}_i \cdot \left(\frac{1 + \text{if}}{1 + \text{in}} \right) \cdot \left(1 - \left(\frac{1 + \text{if}}{1 + \text{in}} \right)^{\text{PL}} \right) \tag{12}$$

$$\text{CRC} = \sum_{i=1}^{n_r} \left(N_r \cdot \text{CRC}_i \cdot \left(\frac{1 + \text{if}}{1 + \text{in}} \right)^{\frac{\text{PL} \cdot i}{f_r + 1}} \right) \tag{13}$$

Where, P_{IIC_i} is the investment cost for the i-th component, P_{OMC_i} is the annual OMC for the starting year, if is the inflation rate in Germany, currently at 2.4 %, in is the interest rate taken as 3.40 %, PL is the total project lifespan considered as 30 years, f_r is the frequency at which component replacement occurs during PL, N_r represents the number of energy production system components to replace, and CRC_i is the replacement cost for the i-th component. In this study, the RC of each component is considered equal to IIC while the OMC is considered as 2 % of IIC. As part of economic evaluation, the levelized cost of energy (LCOE) is also calculated and is given in (14):

$$\mathrm{LCOE} = \frac{TNPC}{TEG} \tag{14}$$

Where, TEG represents total energy generated by the energy production system in one year period including solar, wind, geothermal generation plus energy supplied by public grid.

III. Definition of Optimization Problem

In this study, a sizing optimization problem is formulated with total cost minimization as objective under varying level of renewable energy penetration into the energy production system. The mathematical representation of optimization problem is discussed in following subsections and a metaheuristic optimization algorithm is used for optimization. The mathematical formulation of the optimization process is described in (15) to (18): The objective function to be minimized is defined as follows:

$$\mathrm{TNPC} = f(N_{\mathrm{PV}}, N_{\mathrm{WT}}, N_{\mathrm{BT}}, N_{\mathrm{GTW}}) \tag{15}$$

N_{PV}, N_{WT}, N_{BT} and N_{GTW} are the decision variables, which represent the number of solar panels, wind turbines, batteries, and geothermal wells in the energy production system respectively. The number of decision variables changes depending on the specific configuration of the energy production system. The maximum number of decision variables is 4, as given in (15).

The optimization constraints considered in this study include the overall power balance constraint, production limits of energy production system components, BSS safety and the required grid contributions. The power balance constraint at any given time t is modeled for the proposed energy production system as shown in equation (16):

$$P_{\mathrm{PV}} + P_{\mathrm{WT}} + P_{\mathrm{GTG}} + P_{\mathrm{PG}} \pm P_{\mathrm{BSS}} = \mathrm{LD} \tag{16}$$

Where LD(kW) is total load demand, P_{BSS} is charge and discharge power of BSS. Moreover, the sign convention used here follows the direction of energy flow, where positive values indicate energy flowing into the system, and negative values indicate energy flowing out of the system.

The next optimization constraint ensures the safe operation of the BSS by keeping the SOC of the BSS within specified limits, as shown in equation (17). This constraint is essential to ensure efficient operation and to prolong the lifetime of the ESS:

$$SOC_{\mathrm{BSS_{min}}} \leq SOC_{\mathrm{BSS}}(t) \leq SOC_{\mathrm{BSS_{max}}} \tag{17}$$

where $SOC_{\mathrm{BSS_{min}}}$ and $SOC_{\mathrm{BSS_{max}}}$ represent the minimum and maximum allowable SOC for the BSS at any given time t, ensuring that the BSS operates within safe limits. In this study, the values for these limits are set to 10 % and 90 % respectively. The final constraint implemented controls the percentage of electricity purchased from public grid and is modeled as given by (18):

$$\mathrm{REF} \leq \mathrm{REF_{max}} \tag{18}$$

Where REF is the ratio of renewable power generation to total load demand, while REF_{max} denotes the maximum allowed penetration of renewable power into the energy production system. This constraint allows investigation of the effect of increasing or decreasing dependence on the public utility electric grid.

A. Energy Management Strategy

In this study, a rule-based control strategy is implemented to control power flow between different components of proposed energy production system. The detailed scheme is shown in Fig. 2.

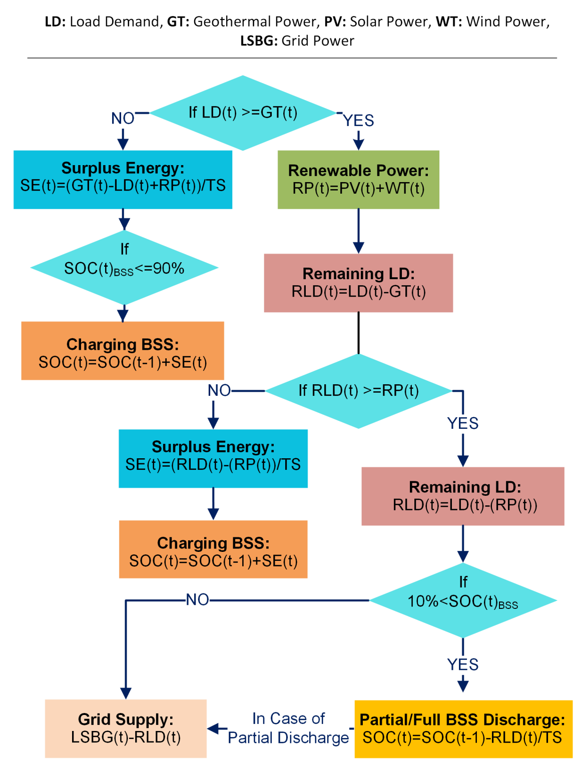

Fig. 2. Decision tree for energy dispatch of energy production system components

IV. Case Study

The KARA accelerator is used as a reference load for designing the energy production system. The proposed energy production system is modeled and simulated over a 1 year period in MATLAB environment with timestep of 1 hour.

A. Description of dataset used

The dataset utilized for the simulation include yearly profiles of LD, SR, WS, and AT as shown in Fig. 3. The SR, AT and WS data is used to generate a power profile of solar and wind generator respectively. The technical specifications and cost data for each component is briefly presented in Table I [18]- [22].

TABLE I
Costs and Specifications of Components of proposed system

Components	**Capacity** (kW)	**Cost** ($/kW)	**Life** (years)	η (%)
Transformer	-	42($/kVA)	30	-
PV Module	0.4	145	30	20.2
LFP Battery	100 (kWh)	108 ($/kWh)	26	95.1
Power Converters	-	300	20	95
WT Generator	1500	1,421	25	-
GT Generator	100	8000	30	12

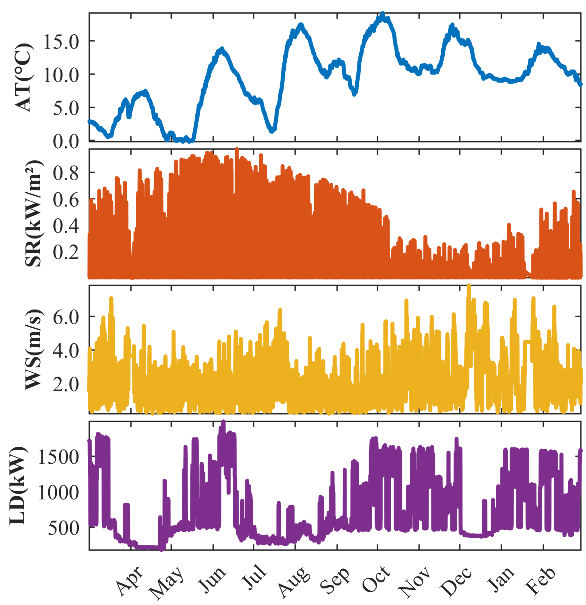

Fig. 3. Hourly profiles of input data over 1-year

B. Optimal Sizing Results

The optimal sizing is directly influenced by the storage requirements and associated costs in all the cases. The results for Case I, which includes PV, WT, and GTGs, are presented in Table II. At lower REFs, the hybridization of PVs and GTGs is optimal as it reduces the large offset cost of adding more WTs compared to PVs. This is because of ease of scalability and modularity of PV modules as the low cost and small capacity per module help achieves the target renewable penetration without oversizing the energy production system, avoiding excess capacity costs. Also, because adding high capacity wind turbine may exceed target REF, leading to higher investment that may occur due to additional storage requirements. For instance, at 10 % REF, Case I requires 1409 PV units, 1 GTG, and no WTs, with no battery storage, leading to a TNPC of $3M. At 30 % REF, the number of PVs increases to 1744, with 2 GTGs and 63 batteries, resulting in a TNPC of $10M. However, at higher REF values, the introduction of WTs becomes more cost-effective than PVs. For example, at 60 % REF, Case I includes 2 WTs, 6355 PVs, and 1711 batteries, resulting in a TNPC of $65M. This shift occurs because to achieve higher penetration of renewable energy, increasing the WTs is more cost effective due to its large per unit capacity even though it is expensive compared to PV modules. In simpler words, a fewer WTs are needed to meet large renewable energy demand as WT high energy yield reduces the overall installed capacity needed to meet LD, offsetting its higher upfront cost. On the other hand, the steady increase in GTGs, evident across all REF levels reflects its cost effectiveness as a base load source. The constant supply of power reduces dependency on local storage and thus contribute to overall cost reduction. For instance, at 100 % REF, Case I requires 5 GTGs, 5242 batteries, and no WTs, achieving a TNPC of $209M.

TABLE II
Case I Configuration and TNPC for Different REF Values

REF	N_{PV}	N_{WT}	N_{GTG}	N_{BT}	TNPC	LCOE
0.0	1409	0	1	0	3	0.3571
0.1	3069	0	1	18	4	0.5913
0.2	1744	0	2	63	10	1.4410
0.3	1790	0	3	479	26	3.8059
0.4	5126	0	3	1188	44	6.4433
0.5	6355	2	3	1711	65	9.6798
0.6	5525	2	4	2555	94	13.9210
0.7	0	1	6	3302	133	19.5410
0.8	0	4	6	4063	165	24.0590
0.9	0	5	7	5242	209	29.5830

The second configuration, which excludes intermittent renewable sources like solar and wind, shows a different trend as seen in Table III. As REF increases, the required GTGs and associated storage units increases linearly. However, compared to Case I, the required storage units remain lower up to 70 % REF, reflecting the reduced variability in energy generation due to absence of PV and WT generators. For example, at 40 % REF, Case II requires 4 GTGs and 436 batteries, resulting in a TNPC of $30M, compared to Case I's 3 GTGs and 479 batteries at a TNPC of $26M. Beyond 80 % REF, the storage requirements in Case II surpass those of Case I due to much larger surplus energy generated from increased GTG capacity. For instance, at 90 % REF, Case II requires 4809 batteries, compared to 4063 batteries in Case I, resulting in a higher TNPC of $180M versus $165M. Although, the absence of intermittent generation might save up costs in storage needs but the higher initial costs of geothermal and its stable supply leads to higher overall costs for providing the same target REF.

TABLE III
CASE II CONFIGURATION AND TNPC FOR DIFFERENT REF VALUES

REF	N_{PV}	N_{WT}	N_{GTG}	N_{BT}	TNPC	LCOE
0.0	0	0	1	0	3	0.3638
0.1	0	0	2	17	7	1.0268
0.2	0	0	3	58	14	1.9743
0.3	0	0	4	436	30	4.4180
0.4	0	0	4	982	48	7.0166
0.5	0	0	5	1685	74	10.9580
0.6	0	0	6	2433	104	15.2870
0.7	0	0	7	3416	140	20.6140
0.8	0	0	7	4809	180	26.3000
0.9	0	0	8	8517	282	40.8590

In Case III, which excludes GTGs, there is a linear increase in required PVs, WTs, and storage units, as seen in Table IV. For example, at 20 % REF, Case III requires 8232 PVs and 106 batteries, leading to a TNPC of \$7M, compared to 3069 PVs and 18 batteries in Case I, with a TNPC of \$4M. Similarly, at 60 % REF, Case III demands 17614 PVs, 6 WTs, and 2891 batteries, resulting in a TNPC of \$100M, compared to Case I's 6355 PVs, 2 WTs, and 1711 batteries, with a TNPC of \$65M.A similar trend to Case I is observed for WTs at lower REF levels, where integrating WTs is not cost-effective and leads to oversizing. For example, at 50 % REF, Case III includes 3 WTs, compared to no WTs in Case I, resulting in a TNPC of \$66M versus \$44M. Furthermore, the absence of constant power supply units in Case III leads to a higher number of required batteries. At 100 % REF, Case III requires 21382 PVs, 17 WTs, and 11260 batteries, resulting in a TNPC of \$343M, compared to Case I's 5242 batteries and \$209M TNPC.

TABLE IV
CASE III CONFIGURATION AND TNPC FOR DIFFERENT REF VALUES

REF	N_{PV}	N_{WT}	N_{GTG}	N_{BT}	TNPC	LCOE
0.0	4116	0	0	19	4	0.4551
0.1	8232	0	0	106	7	0.9484
0.2	12347	0	0	516	17	2.5307
0.3	16463	0	0	1149	33	4.9127
0.4	16994	3	0	1972	66	9.7607
0.5	17614	6	0	2891	100	14.9470
0.6	19518	8	0	4352	143	21.3550
0.7	20133	11	0	6647	210	31.2580
0.8	20752	14	0	8951	276	40.2780
0.9	21382	17	0	11260	343	47.6670

The similar cost trend is also evident by cost of energy generation for each of these systems as can also be seen in Fig. 4.

V. CONCLUSION

The growing concerns about significant carbon footprint and increasing electricity demand of large research infrastructures necessitates the need for local green electricity generation. For this purpose, this study implemented a framework for optimal sizing of a renewable based grid connected energy production system for the Karlsruhe Research Accelerator under varying

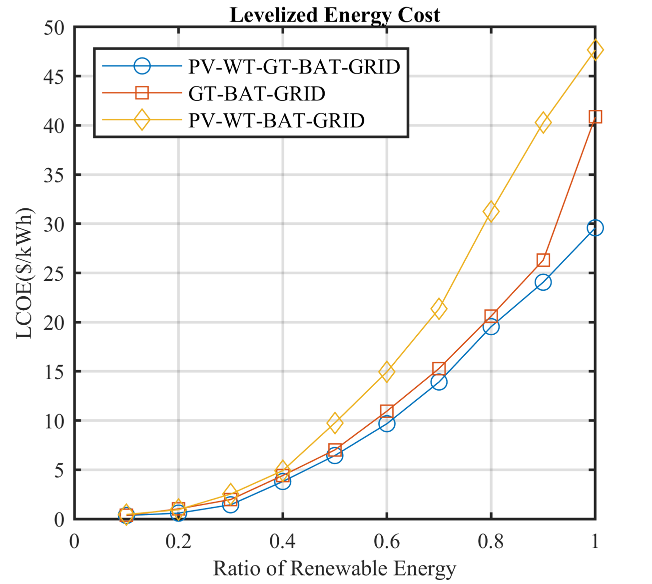

Fig. 4. Variation in LCOE of energy production system based on different maximum allowed REF

level of renewable energy generation. The three distinct configurations of proposed energy production systems are compared based on total net present cost and the trends analyzed in results highlight the trade-offs between total system cost and renewable energy integration in energy production system design. The comparison of LCOE reveals that the highest costs are associated with Case III (no geothermal plant), followed by Case II (no solar and wind generators), while the lowest costs are achieved by the hybrid configuration in Case I.

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