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Energy Reduction and Peak shifting on a Network of Cranes

Feras Alasali [1], Antonio Luque [1], Victor Becerra [2], William Holderbaum[3]

[1]School of Systems Engineering, University of Reading, Reading, Berkshire, UK

[2]School of Engineering, University of Portsmouth, Anglesea Road, Portsmouth, UK

[3]School of Science & Engineering, Manchester metropolitan University, Chester Street, Manchester, UK

E mail: F.m.m.alasali@student.reading.ac.uk

Abstract

Ports around the world are facing significant challenges with rising energy consumption and greenhouse gases due to increasing quantity of international trade. To reduce the environmental effects of emissions and substation peak demand problems in ports, a number of simulation studies have been carried out using data from Port of Felixstowe. The aim of this paper is to propose simulation models of Electrified Rubber Tyre Gantry (eRTG) with Energy Storage Systems (ESS) located at the secondary substation that supplies a network of cranes. Two different conditions are proposed based on whether or not there is t an Active Front End (AFE) to reduce the energy consumption, peak demand and ESS cost. This paper demonstrates through simulations the benefits of adding ESSs with AFEs to regenerate energy into the network recovered from lowering containers and without AFEs for peak shifting.

Keywords: Energy storage systems; Energy consumption; Energy saving; Rubber Tyred Gantry Cranes; Active front-end rectifier.

1. Introduction

Rubber Tyred Gantry (RTG) crane is used for stacking containers in terminals and is usually powered by a diesel generator. About 54% of the container traffic volume in the United Kingdom will increase in next 15 years [1], [2]. Furthermore, this may increase the total power consumption of container terminals as well as the volume of CO2 emissions. Environmentally and economically, the reduction of the power consumption in ports is becoming crucial [3]. Recently, to reduce the gas emissions ports are shifting towards electrified RTG cranes which are connected to the electrical grid [1], [3]. However, when an RTG is lifting mode the hoist motor will consume power and when is lowered, the container's potential energy is converted into electrical form by the hoist motor, but this excess energy is normally dissipated as heat in resistor banks. This includes a significant portion of the energy can be saved by using Energy storage systems or the Active Front Ends (AFEs) along with appropriate energy management [2]–[6]. [6]–[9] develop a crane model based on connecting the ESSs and AFEs to the DC bus system on each crane and using different control method to increase the ESSs efficiency. Simulation studies on eRTG cranes with energy storage systems or Active Front-End rectifiers have shown potential a significant energy savings up to 40% on the wasted energy [3][4]. This paper introduces the design and results of the network of cranes simulations with one ESSs located at the substation and two eRTGs on the network with or without AFE, as shown in Figure 1. This simulation will assess whether a ESSs on the substation could offer benefits to reduce the peak demand, energy consumption and overall cost by using only one ESS at the substation instead of one ESS in each crane.

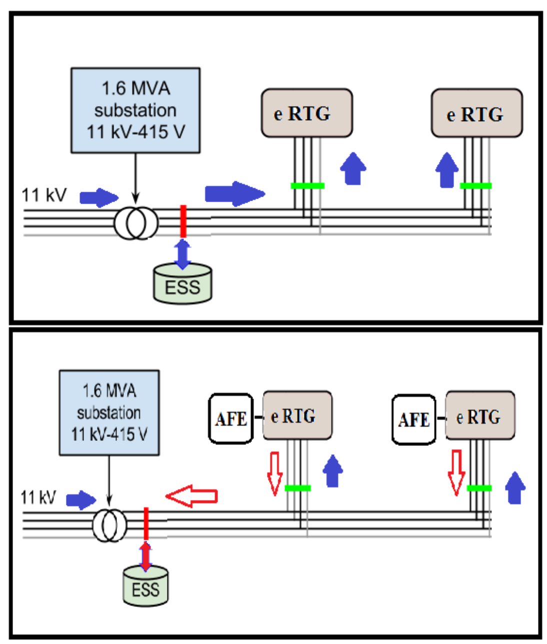

Fig. 1. Diagrams of two Cranes equipped with / without AFE and ESS.

2. Network of Cranes and Energy storage system

A. Network of Cranes at Port of Felixstowe.

Over the last 5 years, Port of Felixstowe and University of Reading have been working to reduce gases emissions in Port of Felixstowe by converting the diesel RTGs to eRTGs and connecting them to the existing electrical network [5],[9]. The University of Reading have been researching methods to reduce power demand and the impact of connecting eRTG to the existing power network. The Port of Felixstowe substations details are shown in table 1. To simplify the simulation of the port electrical network, this paper has investigated the ESS scheme located at the secondary substation with two eRTGs in series with and without the AFE scheme.

Table 1: Characteristics of Port of Felixstowe substations.

Item	Primary Substation	Secondary Substation
Rating	7.5 MVA	1.6 MVA
Voltage	33/11 kV	11KV/415V
Used to	provide power to the secondary substations.	provide power to the eRTGs.
connection	the secondary ‘eRTGs feeder’ substation is connected in series to the primary	

The Port of Felixstowe has chosen a specific conductor rail technology produced by VAHLE to connect the eRTGs to the feeder substation, as it is shown in Figure 2. This allow to move along the conductor rail without electrical connection issues whilst still being able to lift containers of up 40 tones.

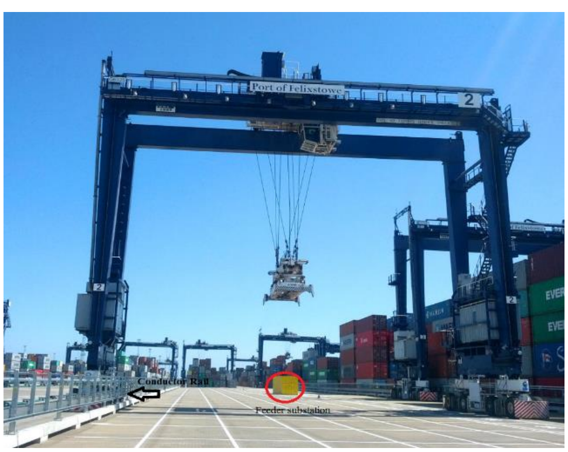

Fig. 2: eRTG crane in Port of Felixstowe

B. E-RTG model

The RTG crane model consists of the main electric equipment which are responsible for power flows:

- Hoist motor (200 kW, four-quadrant drive).
- Brake resistors (when the RTG DC bus voltage exceeds 750 V, the crane will start wasting energy through break resistor).
- DC bus.

A model of an RTG crane developed in [6], [10] and [11] has been modified by two ways:

- First model: replacing the existing diode rectifier with an AFE and adding ESS on the substation to reduce the peck demand by saving the wasted energy during carne lowering mode.
- Second Model: adding one ESS located at the secondary substation side to reduce peak demand without AFEs.

Figure 3 shown the main component of RTG crane and power flow direction [6], [10].

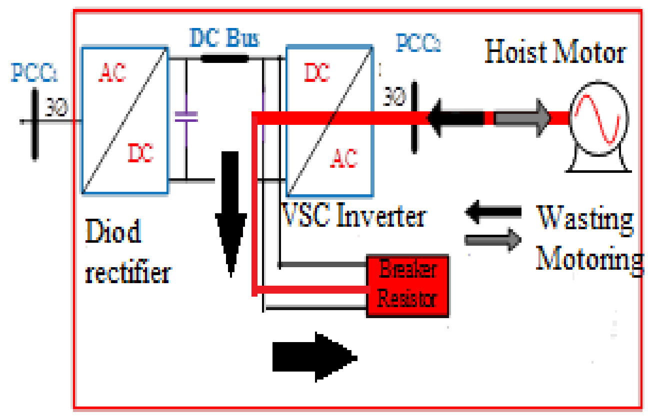

Fig. 3: Simplified Diagram of the main components of eRTG crane.

C. Energy Storage Systems

1) ESS location.

In this paper, the ESS is located on the secondary substation instead of each crane and it will feed into two cranes connecting in series. This design aim to:

- Reduce the standby loss when the crane is not use.
- Reduce the overall cost.
- Peak shifting and reduction on the substation where the energy reduction on the single crane may not lead to reduce the peak demand of the substation.

2) Network of Cranes Models and Control System Scenario:

2.1) First Model :One main ESS with AFEs.

The eRTG cranes could have a significant amount of power loss dissipated into heat in break resistor, allows for the introduction of AFEs. The main aim is to use the AFEs to recover this energy when lowering containers and store it in the ESS. Thus, the ESS can be as a secondary power source to feed the network of cranes by re-using the recover energy during substation peak demand period, as it is shown in Figure 4.

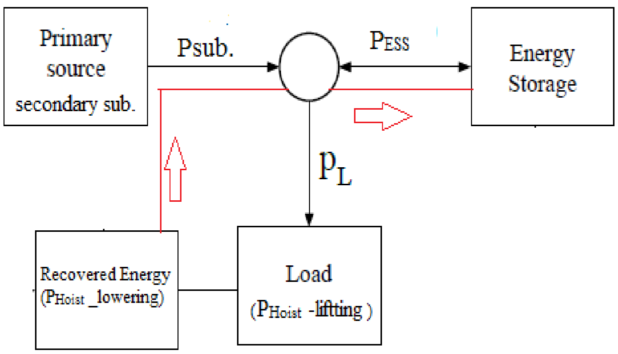

Fig. 4: Topology of the power system (First model).

This reduction directly translates into a reduction in electrical bills and CO2 emissions. In this paper the impact of having an AFE with ESS located at substation to reduce energy consumption and peak demand on the network of cranes is analysed by simulating the activity of an eRTG crane supported by real data collected at the Port of Felixstowe, UK.

An AFE is integrated into the crane model using a voltage source converter. Figure 5 shown the voltage source converter control system developed in [12]-[18] which has been amended for the use in an eRTG cranes and only bidirectional proficiencies of the AFE have introduced.

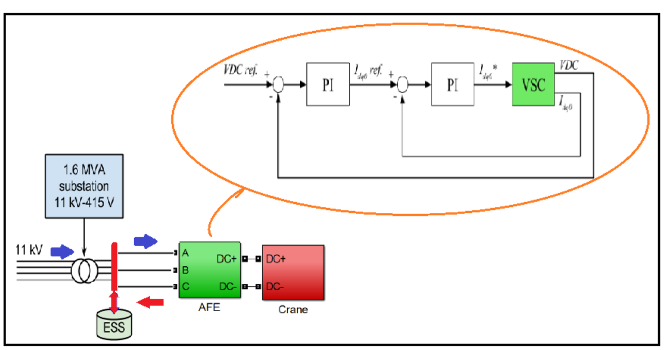

Fig. 5. Voltage source converter control system used in the model [6].

In this paper, the DC bus voltage will be controlled by setting the reference current of the voltage source converter in the dq_0 coordinate system. In order to control the DC voltage, a PI controller reads the difference between the DC voltage and reference voltage (voltage error) and directly sets the i_d reference current. In addition, i_{ref} in the dq_0 coordinate is fed to a second PI controller that controls the current flow through the voltage source converter [10], [15], [16].

A standard model of crane is fitted with a diode rectifier and the DC voltage decreases during lifting mode due to the hoist motor consume power; the voltage then rises when the motor regenerates into the DC bus during the lowering phase. Finally, the break resistors will reach the voltage threshold at 750 V. The power transfer from the secondary substation to the crane when the hoist motor is consuming power during a lifting phase (positive i_d and positive power) and it will move in the opposite direction during a lowering (negative i_d and power). A crane equipped with the modelled AFE will not see the DC bus voltage deviating significantly from the constant value due to the controller action. The main aim of AFE is to effectively prevent dissipating energy through the brake resistors by not allowing the DC bus voltage to reach the threshold value (750 V) [6], [20].

The ESS in this model is charging power during the lowering phase and storing the regenerative energy from AFE. The ESS will be discharging power when the container is lifting and consuming more power. This setting has the potential to reduce the overall power consumption and peak demand in the network of cranes, especially the ESS will store the recovery energy from all eRTG cranes and fed it to network during the higher demand. This may reduce the standalone loss of ESS compared with installed ESS in each crane and reduce the overall peak demand on the substation.

2.2) Second Model :One main ESS without AFEs

The Port of Felixstowe plan is to convert 58 diesel RTGs to eRTGs and connect them to the existing electrical network. This conversion may lead to increase the peak demand and their need to have new substation. However, they have problem to find a suitable location for these substations and also it is costly. This simulation model introduce a main ESS in substation will feed the network during peak period [17]-[19].

The ESS is charging power from the electrical network during the peak off period and is discharging power during peak demand. The peak demand usually will be high during the lifting phase in the crane and will be the opposite during the lowering mode.

However, this model will not introduce any solution for the wasted energy in break resistor and only will focus on reduce the peak demand.

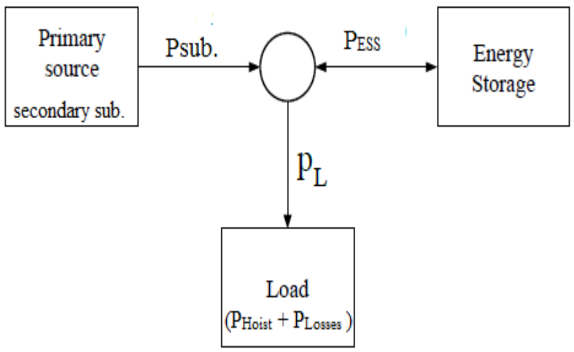

Fig. 6: Topology of the power system (Second model).

3) Flywheel Energy Storage

This section introduces the mathematical equations that govern the ESS and in particular the flywheel storage. Flywheel Energy Storage Systems (FESSs) in particular have been found particularly suited for the simulation model due to it is fast power response and need short time for recharge [14, 18].

A flywheel ESS is a mechanical adaptation and it is stored in the object in kinetic form. The amount of kinetic energy stored in the flywheels ESS is a function of its rotational velocity of the flywheel and mass which can expressed through following equation [9, 11].

$$E = \frac{1}{2} m v^2 \qquad (1)$$

where E is the kinetic energy, m is the mass and v is the velocity. The flywheel discharged function can be introduce by the below formula [7, 16]:

$$E_{discharge} = \frac{1}{2} J(\omega_2^{\,2} - \omega_1^{\,2}) \qquad (2)$$

where $E_{discharge}$ is the discharge energy and ω_1 are the initial energy stored and angular velocity $(rads/s)$ respectively; and ω^2 are the final energy stored angular velocity $(rads/s)$ respectively.

3. Simulation.

A. Model Parmeters

The secondary substation peak demand and energy savings in this paper was tested on a model of an eRTG crane equipped with a flywheel energy storage system. The simulation models parameters are present in Table 2:

Table 2: Initial Parameter Values for the Simulink Simulations

Port Scheme		
Parameter	Value	
Primary Substation	7.5	MVA
Feeder Substation	1.6	MVA
Hoist Motor	250	kW
ESS	10	MJ
AFE	150	kW
AC Filter	7.5	MVAr
kp_1	1.25	
ki_1	1.5	
kp_2	0.001	
ki_2	0.0001	
The i_q and i_0 reference values are set to 0.		

B. Simulation Results

Figure 7 present Simulink model of network of the cranes equipped with an AFE and the result when the ESS is installed in the secondary substation. The primary and secondary substation peak performance are shown in Figure 8a) and Fig. 8b) during the lifting container without AFE and without ESS. From Figure 9 there is a clear difference between peak demand with and without the ESS and AFE. This figure presents an important decrease in power when the AFE regenerate the power during lowering mode and ESS stored then delivers it during lifting mode (peak demand). Figures 8 and 9 show the active and reactive power profiles of the primary and secondary substation. However, both figures show a small transient at the beginning of the period. The ESS location near the substation and it using the regenerative energy to charging ESS may cause this transient. This may affect the life span or could create future maintenance problems of both ESS and AFEs.

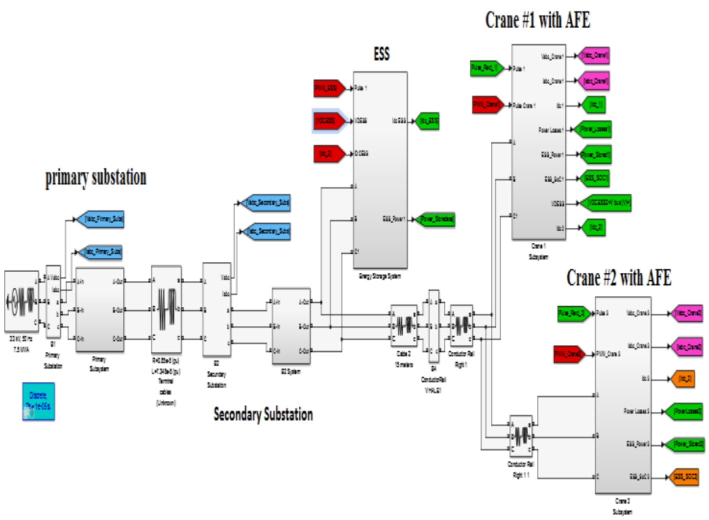

Fig. 7: Simulink model of network of cranes equipped with an AFE and ESS (First model).

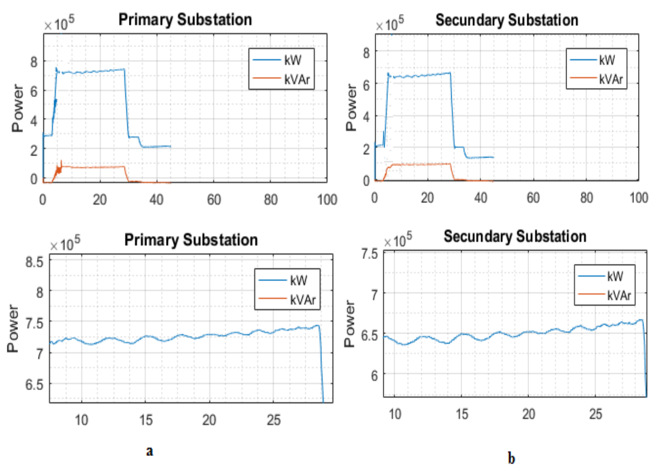

Fig. 8: The primary and secondary substation peak performance without an AFE and ESS.

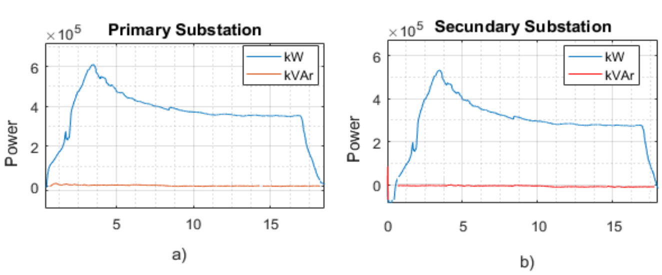

Fig. 9: The primary and secondary substation peak performance with an AFE and ESS (First Model).

The necessary substation data input have been shown at figure 7 and 8. The the peak demand of the both substation without ESS and AFEs was introduce in Figure 8 with a 740 kW for the primary substation and 650 KW for the secondary substation form 5s to 29s (24s peak time). In Figure 9a) and in Figure 9b) reaches around 600 kW and 520 kW as maximum demand value in the substations respectively, with same peak time period (24s). However, the ESS was totally discarded at begging of this simulation and the grid needs to supply the full demand during the initial of the lifting mode.

Figure 10 shows the Simulink model of network of cranes crane with ESS and without AFEs and the ESS located at the secondary substation. The primary and secondary substation peak performance are shown in Figure 11a) and Fig. 11b) during the lifting container (Peak period) with ESS without AFE.

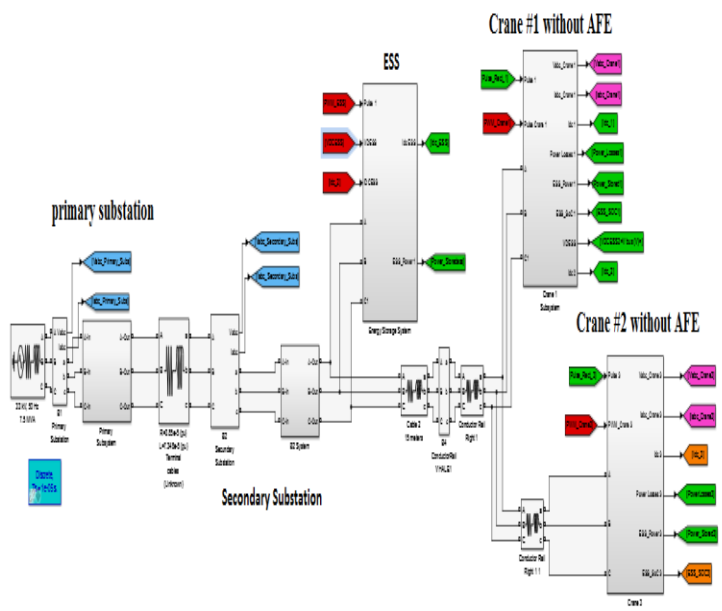

Fig. 10: Simulink model of network of cranes equipped with ESS and without AFE (Second model).

In this model, the ESS has been used to reduce the peak demand in the substation. In addition, the ESS will be charge during lower demand and discharge during the peak demand and due to this the first time period the substation need to feed the full demand of network. From figure 11 the peak demand was reduced in the second time period ,40s to 65s. In figure 11a) and b) shown that the peak period in both substations divided to two parts, the first part from 40s to 48s when the ESS was sharing the load with substation. In this period of time the peak demand in both substations reduced from around

740 KW and 650 KW to 600 KW and 520 KW respectively. The second part of the peak period, the power demand increases suddenly from 48s to 65s. This shows that the ESS is almost totally discharged and substation need to supply the total demand.

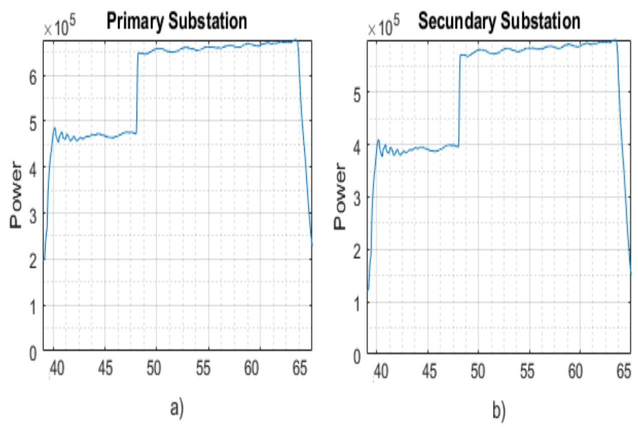

Fig. 11: The primary and secondary substation peak performance with ESS and without an AFE (Second Model).

C. *Analysis of the results*

The simulations produced different results depending on the scenario, with the presence of the storage resulting in reduced energy consumption, as shown in Figure 9. It is clear, without storage, the crane wasted a significant amount of energy in the brake resistors, as all of the potential energy recovered from lowering the container is not being stored.

Table 3 and 4 showed the peak reduction at the primary and secondary substation during one peak period cycle.

Table 3: Maximum Peak demand value

Item	Primary Substation	Secondary Substation
Standard Model (without AFE and ESS).	740 KW	650 KW
First Model (With AFE and ESS)	600 KW	520 KW
Second Model (with ESS and without AFE)	680 KW	600 KW

The reduction in peak demand reached by the proposed models reduce the stress on the primary and secondary substation with more than 4% of the substation operation time under peak period and this is may cause problems in the future for adding a new eRTG on the network. In addition, this has the potential for further reductions in electrical bills and the capital cost for a new substations and reduce the number of ESS. This is cleared in Table 4, where the percentage of time that the substations are more than 500 kW for one hour simulation is shown.

Table 4. Percentage of time that the primary and secondary substation is over 500 kW.

Item	Primary Substation	Secondary Substation
Standard Model (without AFE and ESS)	4.41%	4.07%
First Model (With AFE and ESS)	1.55%	1.02%
Second Model (with ESS and without AFE)	2.93%	2.65%

4. Conclusions

This paper introduced two simulation models to study the potential amount of energy savings and the reduction of peak power demand that can be achieved through regeneration, storage and energy management. The ESS has stored the regenerative energy in the first model and re-uses it during the peak demand (Lifting mode). The second case study introduces the ESS without AFE connected to secondary substation to reduce the peak demand. In this model, ESS will be charge during lower demand period and discharge during peak demand. However, the peak period time and value is mainly related to the crane behavior (lifting or lowering phase). Both scenarios have achieved peak reduction and the first scheme has shown the ability of regenerating the energy and has the potential of decreasing the energy consumption in substations. The results showed that the simulations need further investigation to avoid the transient problems and increase the energy saving. Future work using fuzzy logic, load forecasting and other control strategies could increase the efficiency of the strategy.

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Commonwealth Energy and Sustainable Development Network (CESD-Net)

CESD-Net is a major global initiative in energy and sustainable development. The objective of network is to promote energy and sustainable development in commonwealth countries.
Focussing on Multidisciplinary Research, Promoting Future Low Carbon Innovations, Transferring Knowledge and Stimulating Networking among Stakeholders to Ensure the UK Achieves World Leading Status in Energy and Sustainable Development. https://www.weentech.co.uk/cesd-net/

The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:
Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.
Dr. Kumar is visiting faculty at Prince of Songkla University, Thailand. He have 16 years of research and teaching experience in the field of solar energy, drying and energy efficiency.

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