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Proceedings
Message from the Executive Committee

Welcome to the World Congress on Sustainable Technologies (WCST-2016) in London, UK. The WCST-2016 provides opportunity for academicians and professionals to bridge the knowledge gap and to promote research esteem.

The WCST-2016 received 210 papers from 32 countries of which 53 papers were accepted after the first review and 29 papers (extended abstracts 7 and full papers 22) were finally accepted for presentation. We received 13 Posters and 5 were accepted and 4 workshops were accepted out 9. The double blind paper review method was adopted in WCST-2016 to evaluate each of the conferences submissions. Please note that selected papers will be invited for publications in high impact International Journals.

Many people have worked very hard to make this conference possible. We would like to thank all who have helped in making WCST-2016 a success. The Steering Committee and reviewers each deserve credit for their excellent job. We thank the authors who have contributed to each of the conferences. We will also like to acknowledge our appreciation to the following organisations for their sponsorship and support: Infonomics Society, IEEE UK/RI Computer Chapter and Canadian Teacher Magazine. The long term goal of WCST-2016 is to build a reputation and respectable conference for the international community.

On behalf of the WCST-2016 Executive members, we would like to encourage you to contribute to the future of WCST-2016 as authors, speakers, panellists, and volunteer conference organisers. We wish you a pleasant stay in London, and please feel free to exchange ideas with other colleagues.

Julius A. Fapohunda, Cape Peninsula University of Technology (CPUT), South Africa
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Valentina Colla, Scuola Superiore Sant’ Anna - TeCIP Institute, Pisa, Italy
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Keynote Speakers
and
Track Speaker
Keynote Speaker 1

Martin Visser has over 35 years of experience in the Industrial Control Systems (ICS) environment. From engineer, process information expert, project leader and ICS consultant to Security Officer Industrial Control Systems. Martin has worked for Waternet for more than 30 years. For the last 10 years, Martin was responsible for the security of the entire ICS architecture, Supervisory Control And Data Acquisition (SCADA) and Programmable Logic Controller (PLC) systems of Waternet. His work consisted of drawing up security policies, conducting risk and GAP analysis and assessments. Compiling and executing security awareness training programs and giving ICS advisories. Providing ICS security presentations at home and abroad. From 2006 Martin have been the vice chairman of the Dutch Water-ISAC. In addition he was ICS security consultant for the Dutch association of Drinking Water Companies and Dutch Waterboards and regularly attended ministerial ICS security working groups. Martin have been member of the security working group of the WIB (International Instrument User’s Association). The WIB is the founder of the IEC62443-2-4 norm that describes the baseline security standards and certification for ICS suppliers. In August 2015 Martin voluntarily resigned from Waternet. At the same time he founded BeeCA, Bee Cyber Aware, Consultancy to continue my challenging and interesting cyber security work. BeeCA is an advisory and consultancy office in Cyber security, Cyber awareness and Information security for SCADA, ICS, PLC and Operational Technology (OT). As ICS expert/consultant Martin have a strong focus on cyber security for all aspects of Industrial Control Systems in critical infrastructures (utility, drinking- and sewage water, energy).

Title: Critical Infrastructures SMART ready?

Abstract: The EU initiatives for Research and Innovation for excellent science, competitive industries and a better society together with the new Industry possibilities from Internet of Things and SMART technology putting the Critical Infrastructures in addition to the advantages also for technical, organizational and Industrial Control Systems security challenges. In this keynote I will highlight all these parts as well as the cyber risks and threats in relation to the social responsibility, disruption and economical damage. To complete the keynote I will give some key points to take away and think back over again after returning to your institutions or businesses.
Keynote Speaker 2

Dr Julius Ayodeji Fapohunda is a senior lecturer in the Department of Construction Management and Quantity Surveyor, Cape Peninsula University of Technology (CPUT), Faculty of Engineering. He obtained his PhD in Construction Management at Sheffield Hallam University, Sheffield, MSc in Building (with specialisation in Construction Management) at University of Lagos, BSc (Hons) in Building with second class upper division at University of Jos and National Diploma in Building Technology at Federal Polytechnic, Ilaro, Nigeria. Dr Julius Ayodeji Fapohunda is a recipient of many academic awards, among which are Platinum Award in Research Output at Cape Peninsula University of Technology for the year 2015; the Best Reviewer Award from the ‘Journal of Engineering, Design and Technology’ in 2013: Academic Excellent Scholarship Award for the Best Student in Building Department, University of Jos, Jos, Nigeria, 1988 and the Best Graduating Student Award (National Diploma), Building Technology Department, Federal Polytechnic, Ilaro, Nigeria, 1987; and. He is a member of many professional associations which include: Nigeria Institute of Building (MNIOB), Nigeria; Council of Registered Builders (CORBON), Nigeria; Nigeria Institute of management, (NIM), Nigeria; Association of Project Management (APM), UK, Chartered Institute of Building, (CIOB). Over a decade, he has practiced as a Construction Project Manager, Project Management Consultant, Building Entrepreneurs’ Developer and Trainer, Researcher and Lecturer.

Title: Global Acceptability of Sustainable Innovative Concepts: Rethinking Sustainability

Abstract: All nations are challenged to meet the concept of sustainability. While there is a need to balance the 3 concerns of the sustainability concepts, (Social, Economy and Environmental securities), there are major economic, social and cultural differences and inequalities across nations and regions. Thus, sustainability challenges are unique in both developing and developed nations, based on where each nation places emphasis, importance and on each nation's position, situation and needs. The concern is: ‘could any of the Sustainable Innovative Development Targets be met?’ In addition, since this concept has emerged (over decades) through Bruntland Report for the World Commission on Environment and Development (1992), ‘what are the impacts of accepting sustainability concepts on individual human/country? This paper significantly evaluates the global positions of sustainable innovative concepts and asserts sustainable concepts as a catalyst for continuous innovation towards meeting human needs. The author emphasised that SDGs/targets are necessities, aimed towards enhancement or meeting human needs. However, human needs are infinite and insatiable. Thus, Sustainable Development targets are innovative concepts for better living /life at present and set standard for future re-evaluation.
Track Speaker

Dr Tramontin holds a PhD in Building Engineering from the University of Cagliari (Italy). At the same University, he taught Building Technology at the Faculty of Architecture and was a two-year Research Fellow. He worked at UKZN as a Post-Doctoral researcher and in 2014 he joined the Property Development Programme as a Lecturer. His research focuses on green building and green infrastructure in developing countries, passive design and energy efficiency in buildings, sustainable construction technology. He worked for 7 years as a Professional Architectural Engineer and consultant in Italy. He is a Green Star South Africa Accredited Professional (New Buildings) from the Green Building Council of South Africa.

Title: Implementing a holistic approach to foster higher education for sustainability.

Abstract: The adoption of sustainable practices in the built environment requires the professionals working in the Architecture, Engineering and Construction industry to acquire new competencies, particularly in developing countries that have committed to a new agenda for a more sustainable future. The role of higher education is vital to promote sustainable development principles as fundamental drivers within the curricula of the relevant disciplines, in order to equip graduates with the necessary skills to implement sustainable practices and strategies of resource efficiency in their future career. The assessment of the findings from previous studies conducted at the University of KwaZulu-Natal (UKZN) in Durban, South Africa, highlighted the importance of incorporating principles of sustainability and energy efficiency into built environment-related curricula of higher education. Following a holistic approach, the greenUKZN (Green Regeneration, Environmental and Energy Upgrade at UKZN) research programme has been proposed as a possible strategy towards achieving this target. GreenUKZN is a multidisciplinary programme led by the School of Engineering of UKZN joining research, teaching and learning, energy management and sustainability upgrade initiatives of university’s buildings and facilities, which utilizes the university campuses as an experimental field for the investigation and the implementation of sustainable practices and resource efficient strategies.
Implementing a holistic approach to foster higher education for sustainability

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Abstract—The adoption of sustainable practices in the built environment requires the professionals working in the Architecture, Engineering and Construction industry to acquire new competencies, particularly in developing countries that have committed to a new agenda for a more sustainable future. The role of higher education is vital to promote sustainable development principles as fundamental drivers within the curricula of the relevant disciplines, in order to equip graduates with the necessary skills to implement sustainable practices and strategies of resource efficiency in their future career. The implementation of new competencies, particularly in developing countries that have committed to a new agenda for a more sustainable future. The role of higher education is vital to promote sustainable development principles as fundamental drivers within the curricula of the relevant disciplines, in order to equip graduates with the necessary skills to implement sustainable practices and strategies of resource efficiency in their future career. The assessment of the findings from previous studies conducted at the University of KwaZulu-Natal (UKZN) in Durban, South Africa, highlighted the importance of incorporating principles of sustainability and energy efficiency into built environment-related curricula of higher education. Following a holistic approach, the greenUKZN (Green Regeneration, Environmental and Energy Upgrade at UKZN) research programme has been proposed as a possible strategy towards achieving this target. GreenUKZN is a multidisciplinary programme led by the School of Engineering of UKZN joining research, teaching and learning, energy management and sustainability upgrade initiatives of university’s buildings and facilities, which utilizes the university campuses as an experimental field for the investigation and the implementation of sustainable practices and resource efficient strategies.

Keywords—Sustainability Education, Developing Countries, Energy Efficiency, Resource Efficiency.

I. INTRODUCTION AND BACKGROUND

Dealing with the topic of sustainability in Architecture, Engineering and Construction disciplines requires that professionals address built environment problems from multiple perspectives, including various and conflicting viewpoints [1]. Strong critical thinking, problem solving skills and interdisciplinary competencies are required by the relevant professionals in order to implement sustainable strategies in their practice. With particular regard to the theme of sustainability, in fact, knowledge cannot be considered as cumulative and linear, but must be intended “as a nesting and interacting of frameworks” [2] which must be addressed through a holistic and integrated approach.

The lack of capacity of the construction sector to implement sustainable practices was observed as one of the major barriers to sustainable construction in developing countries [3]. This

assumes particular importance for those countries, such as South Africa, which have decisively committed to a new agenda to promote a more sustainable future.

Building such a capacity requires a critical contribution from higher education institutions. Reaching academic excellence, innovation in research, critical engagement with the society implies the need of academia for embracing the challenge of promoting education for sustainable development, reshaping educational models and curricula to incorporate the principles of sustainability, resource conservation and environmental responsibility, and finally aligning the relevant research, teaching and learning agendas. Incorporating in higher education principles of sustainability would also contribute to promote more environmentally and socially responsible citizens, following a “social reform” approach to education [4] aimed to foster learning that is able to promote a better society.

The purpose of the study is to present the innovative and holistic approach to this challenge that has been promoted by the School of Engineering of the University of KwaZulu-Natal (UKZN) in Durban, South Africa, through the proposal of the greenUKZN (Green Regeneration, Environmental and Energy Upgrade at UKZN) programme.

II. METHODOLOGY

A critical assessment of the results of previous empirical studies conducted in the province of KwaZulu-Natal, South Africa, and at UKZN [5] highlighted the importance of incorporating principles of sustainability and energy efficiency in buildings into the relevant higher education curricula. This investigation showed the main challenges to be faced and demonstrated the awareness, from the perspective of both local academics and built environment professionals, of the critical need for an improved higher education focusing on sustainability and energy efficiency issues.

This assessment was complemented by the analysis of the positive outputs from previous research projects oriented to an improved energy management of selected university’s buildings, by an in-depth review of the literature on the topic and through the consultation with academics and leadership positions. In particular, the results achieved by energy management pilot projects implemented at UKZN since 2009 showed the potential that better practices of energy
management, energy and green retrofitting can produce for the institution in terms of energy savings, water savings and relevant operating cost savings.

All these steps contributed to identifying the major barriers and opportunities to foster holistically education for sustainability within the institution, and to develop the strategy that informed the rationale underpinning the greenUKZN programme, its vision and mission, objectives, structure and activities, expected outcomes and benefits, which are summarised in the following sections.

III. DISCUSSION: THE GREENUKZN PROGRAMME

GreenUKZN is a multidisciplinary research, educational, energy and resource management, and green retrofitting programme coordinated by the School of Engineering of UKZN that aims at enhancing the institution by implementing sustainability, energy and resource efficiency principles. The main aim is to create a framework that promotes and links research and education in the field of sustainability with the green and energy upgrade of the university’s buildings and facilities.

The programme has been conceived as an innovative platform oriented to lead the challenge of implementing sustainability and resource efficiency initiatives at multiple levels including research, teaching and learning, energy management and green retrofitting of buildings, by utilizing primarily the campuses as an experimental field for the investigation and the implementation of sustainable and resource efficient strategies.

GreenUKZN will operate as a platform for research projects investigating specific aspects within the field of sustainability, fostering research collaboration and student engagement at undergraduate and postgraduate level. The programme concentrates on the investigation of sustainable practices, energy and resource efficient strategies to improve the university environment. The activities focus, among others, on the following fields: energy efficiency in buildings; sustainable buildings; water efficiency; resource and waste management; energy from waste; green infrastructure; green construction materials; renewable energy systems; indoor environmental quality.

The results of the projects will be utilized to support action plans and implement such practices and measures through resource and energy management, green retrofitting and sustainability upgrade initiatives within the university campuses. The programme primarily aims to a self-financing mechanism by creating a sustainable loop that utilizes the operating cost savings achieved through the increased efficiency of university’s facilities and buildings to finance new research projects and to expand the implementation of green and resource-efficient initiatives to other facilities within the campuses.

The programme promotes the dissemination of the outputs of the research projects to produce teaching and learning material aimed at incorporating sustainability and resource efficiency principles within the relevant curricula, and at reviewing the same curricula in the light of such outcomes and increased awareness of sustainability issues (Fig. 1). The programme will also foster international collaborative projects to promote knowledge and technology transfer that will be beneficial to advance research at UKZN and improve the resource efficiency and environmental quality of the university environment.

IV. CONCLUSIONS

The greenUKZN programme represents an innovative educational approach to holistically address the challenge of promoting the sustainable development through higher education and enhance the social responsibility of the academic institution.

The programme has the potential to: enhance education and foster research activities on these topics; improve the efficiency and the environmental quality of the buildings and spaces across the campuses, reducing relevant operating costs; showcase the benefits of sustainable practices and utilize the university as pilot site with the view of commercialising the technology for roll out to other similar initiatives being explored with the city, industry and local government; improve the competency of graduates in this field; increase the general awareness on the importance of resource conservation and promote the culture of sustainability within the academic and professional environment.

GreenUKZN is promoted as a long-term initiative and will be progressively monitored for auditing purposes in order to evaluate the benefits achieved and implement possible improvement actions.

REFERENCES

PhD and Doctorate Consortium

The idea of writing a research paper or developing a topic of research interest that can lead to a PhD / Doctorate degree or proposal is always an endless thinking of where, when, why, what and who. Therefore, becoming an experienced researcher and writer in any field or discipline takes a great deal of practice. The Consortium has the following objectives:

- Provide a supportive setting for feedback on current research that will stimulate exchange of ideas;
- Guide on the future research directions;
- Promote the development of a supportive community of scholars and a spirit of collaborative research;
- Contribute to the conference goals through interaction with other researchers and conference events.

The PhD and Doctorate Consortium highlights possible solutions in response to the lack of competence demonstrated by young researchers and PhD and Doctorate students, and the understanding of what contributes to knowledge gap.

Organiser: Charles A. Shoniregun, Infonomics Society UK and Ireland
Session 1: Operation, Optimization and Sustainability

Principle and Evaluation of a Self-Adaptive Multi-Agent System for State Estimation of Electrical Distribution Network
(Authors: Alexandre Perles, Guy Camilleri, Marie-Pierre Gleizes, Olivier Chilard, Dominique Croteau)

Energy Sustainability and Management of Data Center
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Principle and Evaluation of a Self-Adaptive Multi-Agent System for State Estimation of Electrical Distribution Network

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Abstract—In our daily life, electricity becomes more and more important. Mainly for environmental concerns, governments tend to encourage integration of generators which rely on renewable energy sources. Therefore, it is necessary to move from present electrical networks to smarter ones. These issues have contributed to the development of the concept of Smart Grid. One might well ask the question: how to add a layer of intelligence on electrical networks as we know them?

The work presented in this paper is mainly focused on the State Estimation as a way to observe the evolution of low voltage or medium voltage disturbances in order to mitigate them using innovative regulation functions. The Atena platform presented in this study has shown the feasibility and some advantages of using an adaptive multi-agent system for the estimation of the network state within a reasonable time, with encouraging accuracy for voltage regulation, with a linear complexity and with the capacity to adapt itself to changes that can occur in the network. Each agent has only a local perception of the grid and interacts with its immediate neighbors according to the network topology, without any information on the global state.

Multi-Agent System; State Estimation; Distribution Network; Smart Grid; Cooperation

I. INTRODUCTION

Before the 1990’s, the state estimation of electrical networks has never been a major concern. Indeed, the way these networks have been designed and dimensioned suits perfectly with the use which has been made of it. However, the ever-growing needs in electricity as well as the environmental concerns have led providers to find smarter ways to produce, distribute and consume energy. Researches around the concept of "Smart Grids" have therefore boomed [1].

In this study, we propose to evaluate the Adaptive Multi-Agent System theory as a candidate for distributing intelligence in electrical networks. In the first place, we will explain why the State Estimation of Distribution Systems is an important and complex problem and review related works which have tried to solve this problem. Secondly, we will present the theory of Adaptive Multi-Agent Systems. Then, through the application of this theory, we will describe the proposed system called Atena (Adaptive Transport of Energy in Networked Areas) aiming at solving this problem. Next, an evaluation of the system will be presented. And finally, we will conclude and discuss perspectives.

II. STATE ESTIMATION IN DISTRIBUTION SYSTEM

A distribution system is the part of an electrical network which distributes electricity from transmission systems to consumers. These systems are made of nodes, also called buses, which are linked with other nodes through lines which may have various admittances. In order to have a power flow in these systems, there must be at least one producer (generator) and at least one consumer (load) each one connected to a bus. For each node to which a producer or a consumer is connected, there is a power sensor (or at least a load-pattern). In addition, some other voltage sensors can be associated with other buses. These sensors provide noisy data about the state of the network.

A. Problem Description

The state estimation problem can be expressed as finding a voltage magnitude and a voltage phase for each node in order to be consistent with the network characteristics (topology, lines admittance ...) and to enable a filtering of data provided by various sensors. More generally, the objective of state estimation is to determine the most likely state of the system based on quantities that are measured which are assumed to have a Gaussian (normal) distribution. One way to accomplish this state estimation is by using the statistic method of maximum likelihood estimation. By assuming the independence of measurements and their Gaussian distribution, determining the state of a network is equivalent to solving an optimization problem where the objective function can be expressed as a sum of Weighted Least Squares.

In case we do not have power sensors associated with a consumer (or a producer), we use load-patterns (or pseudo measurements) generated from load forecasts or historical data. However, the producers are always instrumented with power and voltage magnitude sensors.
It is therefore a question of finding the voltage of nodes that satisfy the model of the network while minimizing the distance between found values and sensed ones.

The problem can be then divided in two parts:

1) Kirchhoff’s Current Law

The first constraint is derived from the Kirchhoff’s current law which must be fulfilled. The power is defined according to the consumption, production and lines power transit at the considered node. By convention, the currents are assumed to flow from the bus to the terminal of each component connected on it.

Fig. 1 represents the current flows between four buses. For bus 2, the Kirchhoff’s Current Law is verified if $I_{24} + I_{21} = 0$. For bus 3, the current of the producer (or consumer) has to be taken into account.

The model retained for each underground or overhead line is provided by Fig. 2. Thus, the current at each bus of a line is entirely determined by (1). The complex values of these currents ($I_1$, $I_2$) depend both on the line node matrix and the voltage complex value at each bus. Let:

- $1$ and $2$ be two buses connected through a line,
- $Y$ be the admittance matrix of the line,
- $V_j$ be the voltage (complex value) of the node $j$,
- $I_j$ be the current flowing from the node $j$ to the line,
- $\text{Variable}^\ast$ be the conjugate of the variable.

The admittance matrix of a line is defined in Table I.

According to (1), the apparent power flow from bus 1 to bus 2 is determined by (2).

$$
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix} =
\begin{bmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
\tag{1}
$$

From this equation, we can deduce (2) to compute the power $S_{12}$ provided by bus 2 through the line to bus 1.

$$
S_{12} = V_1 \cdot (V_1^\ast \cdot Y_{11} + V_2^\ast \cdot Y_{12})
\tag{2}
$$

2) Data to be filtered by state estimator

Sensors are not perfect, their native inaccuracy can have a non-negligible impact on the voltage estimates. The number of measurements has to be limited in order to reduce the costs of the proposed solution. Consequently, active and reactive power pseudo measurements have to be used at each consumption point (load models).
A. Multi-Agent System

A Multi-Agent System is a system in which a certain amount of autonomous entities, called agents, interact with one another and the environment for accomplishing a collective task.

1) Agent

A commonly admitted definition of an agent is that it is an autonomous entity that can be seen as perceiving its environment through sensors and acting on it through effectors [11]. This definition can be completed by telling that an agent can have the ability to communicate with other agents and is able to take decisions on its own [12]. An agent has only a limited view of its environment.

2) Environment

We consider two kinds of environment:

- The environment of the multi-agent system contains everything that is not part of the multi-agent system. When solving an optimization problem, the environment of the multi-agent system is the problem itself;
- The environment of an agent contains the environment of the multi-agent system and some other agents of this system. It is however important to notice that agents perceptions are limited and therefore they are only able to observe a small part of this environment.

3) Adaptive Multi-Agent System Theory

An Adaptive Multi-Agent System (AMAS) is a multi-agent system in which agents have a coherent collective activity to achieve the right task. It has been proved that: "For any functionally adequate system, there is at least a cooperative interior medium system which fulfills an equivalent function in the same environment".

This then introduces the concept of cooperative agent. A cooperative agent is an agent which cooperates with the others in order to satisfy its goals and the ones of its neighbors. As the resolution of the global problem is not implemented in agents, one can talk of emergence [13], [14].

4) Self-organization and Self-Adaptation

The concept of “Emergence” seems to be suitable to conceive adaptive systems for dynamic environments. Emergence and self-organization are similar concepts as they appear to have common characteristics such as non-linearity. Self-organization is a physical and biological notion about the state of some systems able to display functions or structured forms without any outside intervention. This can be understood by the ability for a program to modify its organization without receiving commands from the user. Self-adaptation defines the ability for a system to adapt its structure according to the evolution of its environment in order to keep its normal functioning.

Accordingly to the decentralized nature of the problem and the amount of uncertainties we have on it, the concept of Adaptive Multi-Agent System seems to be a good candidate to solve the state estimation problem.

B. The AMAS Atena

1) Environment of the System

The environment of Atena is the electrical network for which it tries to estimate the state. Based on the terms proposed by Russell and Norvig [11], the environment of Atena can be characterized as being:

- **Inaccessible**: Sensors are not perfect and are limited in number. Furthermore, load patterns are used instead of real measures in order to reduce the costs of deployment;
- **Continuous**: Electrical networks are discontinuous as the retained model neglects transitory states caused by variations of various system variables. However, the various measurements provided to Atena are averaged in a sliding window of 10 minutes. Consequently, the electrical system is considered as continuous;
- **Deterministic**: The Multi-Agent System has an averaged vision of the operating point of the network. From these measurements, the Multi-Agent System estimates this operating point without acting on the electrical system. Therefore, for agents, the environment is considered as deterministic;
- **Dynamic**: As mentioned before, the state of the environment is influenced by various external factors. Thus, even if agents never modify the environment it cannot be guaranteed that this latter will remain the same between two perceptions.

2) Identification of Agents

The identification and characterization of agents for state estimation has to be as close as possible to the various entities of the physical system. Consequently, the system is made of “bus agents”. It seems obvious that this choice will facilitate the design, the understanding and the analysis of the multi-agent system. In addition to this, the system contains resources “Line”. The transit of each line can be calculated according to the current voltage state at each bus on either side of the line.

The internal state of a bus agent is characterized by four real variables: the active power produced (or consumed) $C_P$, the reactive power produced (or consumed) $C_Q$, the voltage magnitude $C_V$, the phase angle $C_\theta$.

Fig. 3 represents an example of an electrical network made of four buses. As we can see, a bus agent is associated with each node.

One objective of a bus agent is to modify its internal state.
to respect the Kirchhoff’s Current Law.

The sum of active and reactive power flows of a bus agent $A_b$ associated with a bus $b$ can be expressed in the following way:

- For active power: $C_p + \text{Re}(\sum_{n \in \text{Neighbors}_b} V_b \cdot (Y(1,1)_{b,n} \cdot V^*_b + Y(1,2)_{b,n} \cdot V^*_n))$
- For reactive power: $C_q + \text{Im}(\sum_{n \in \text{Neighbors}_b} V_b \cdot (Y(1,1)_{b,n} \cdot V^*_b + Y(1,2)_{b,n} \cdot V^*_n))$

With:

- $\text{Neighbors}_a$ the direct neighbors of the agent $A_a$ associated with bus $a$,
- $V^{(\text{current})}_b = C_V \cdot e^{ic\theta}$ the complex number made of the state variables $C_V$ and $C_B$ of the agent $A_b$,
- $Y(i,j)_{b,n}$ the mutual admittance between nodes $i$ and $j$ of the node matrix of the line connected between buses $b$ and $n$,
- $Y(i,i)_{b,n}$ the self-admittance of the node $i$ of the line connected between buses $b$ and $n$.
- $\text{Re}(X)$ and $\text{Im}(X)$ the real and imaginary parts of the complex $X$.

These formulas directly come from (1) where bus $b$ stands for the node 1 and bus $n$ for the node 2.

A function $F$ has been implemented in each agent such as $V^{(\text{new})}_i = F(V^{(\text{current})}_i)$ where $V^{(\text{new})}_i$ is the new voltage of the bus agent $i$ and $V^{(\text{current})}_i$ the old voltage. The application of this function will reduce the sum of weighted least squares which includes implicitly the Kirchhoff’s Current Law.

More precisely, each agent has a local objective function $O$ allowing it to evaluate the distance to its objective. Agents try to minimize it with the Weighted Least Squares method. The function $F$ comes from the derivative of this function $O$.

Fig. 4 presents the state of two bus agents which both have an associated voltage sensor. Each bus agent has a current voltage magnitude estimation represented by a circle. Using the function $F$, they are able to determine if they have to decrease or increase their voltage magnitude. In this example, the agents are unable to make these moves as their respective authorized deviations are too low. In order to do these moves, the agent 1 has to increase its authorized deviation by $\alpha$ while the agent 2 has to increase it by $-\beta$.

As mentioned previously, the state estimation problem is also a balance problem between distances to sensor values. Given the fact that agents’ perceptions are limited, they are not able to benefit directly of data redundancy. Thus, the agents need to cooperate.

In the case where the agents are limited by their authorized voltage deviation (as in Fig. 4), they have to find a compromise with other agents. In other words, if an agent $A$ wants to increase its authorized deviation by $\alpha$, it has to find an agent that will do the same in the opposite way. If the value $|V^{(\text{new})}_i|$ is within the authorized interval or the agent does not have a voltage sensor, the agent can directly use $V^{(\text{new})}_i$ as its new state value. In the case where the $|V^{(\text{new})}_i|$ is outside of the authorized interval, the agent has to send a message to its neighbors to ask them to change their deviation value in the other direction than the one it needs.

3) Neighborhood
The neighborhood of an agent is composed of the set of agents that are directly connected to it. In the field of this study, we consider that two agents are directly connected if it exists a line linking the two buses they are associated with. For example, in Fig. 3, the neighbors of agent A1 are A2 and A3, the neighbors of A2 are A1 and A4, the neighbor of A3 is A1 and the neighbor of A4 is A2. 4)

4) Perception of an agent
An agent is able to perceive two categories of data. The first one is data provided by its neighbors and the second one is data provided by sensors connected to the bus it belongs to. The data that can be perceived from a neighbor is its current voltage magnitude and phase angle estimation. In the case of the presence of a voltage sensor attached to the bus, the agent can perceive the voltage magnitude returned by it and its precision in percent. In the case of the presence of a power sensor (or a pseudo-power sensor), the agent is able to perceive the returned values of active and reactive power and the precision in percent of these values. In addition to these abilities of perceptions, an agent is able to send and receive messages to its neighbors.

5) Behavior
a) Perception
During the perception phase, an agent observes its neighbors and gets the updated information about their voltage magnitude and phase angle estimations. Let us call $V_{P_n}$ the complex made of the data perceived from the neighbor $n$. The agent also gets messages sent by its neighbors since the last perception phase.

b) Decision
At first, in the decision phase, the agent evaluates the result $V^{(\text{new})} = |V^{(\text{new})}| \cdot e^{i\theta^{(\text{new})}}$ of the function $F$ applied to its current representation of its environment.

Let us consider $V = |V^{(\text{current})}| \cdot e^{i\theta^{(\text{current})}}$ the current voltage estimated by the agent.

Figure 4. Example of a situation in which two agents can help each other
In the case where the agent has an associated voltage sensor, it also has an authorized voltage deviation value \( D_v \).

\[ |V^{(\text{new})}| - |V^{(\text{current})}| > D_v \]

means that the value proposed by the function \( F \) exceeds the authorized voltage deviation \( D_v \).

The agent may have received messages from agents which have the same problem.

In this case, the agent has to check if it can modify its authorized voltage deviation to satisfy itself and the others. In the case where the agent has received messages that it does not understand or whose the contained request run contrary to its desire, the agent places them in a temporary stack \( T_s \).

After this process, the value \( D_v \) may have been updated.

c) Action

If the value \( V_{\text{new}} \) is within the authorized voltage range, then the agent sets its state to \( |V^{(\text{new})}| \cdot e^{i\theta^{(\text{new})}} \). On the contrary, the agent sets its state to the closest allowed value: \( (|V^{(\text{current})}| + D_v) \cdot e^{i\theta^{(\text{new})}} \) and broadcasts a help request to its neighbors. Finally, if messages remain in the temporary message stack \( T_s \), the agent broadcasts them to each neighbor except the one which has sent it.

Such a behavior allows agents to cooperate and count on other agents to help them. It is clearly visible that although each agent tries to pursue their own goal, they also have the capacity to help agents which cannot. Therefore, agents will help each other provided that it does not make them more unsatisfied. Talking to this capacity of interactions, we come back to the notion of “emergence”. The self-organization realized by the agents leads the system to provide a solution to a problem agents are not aware of.

Such a behavior allows agents to optimize a weighted least square locally with their neighbors and the cooperation between agents brings the system to tend to a global maximum likelihood.

IV. ATENA EVALUATION

A 64-buses network has been used as a test case. A power and voltage sensor is installed at the slack bus and a pseudo-power sensor is associated with each consumer. For each of the 64 buses, an agent is created, linked with the proper neighboring bus agents.

The system has been evaluated on four criteria:

A. Atena Performance Over the Amount of Voltage Sensors

In this evaluation, we have determined the impact of the number of voltage sensors over the performance using the multi-agent system Atena. The performance of a system is the percentage of successful resolutions over the total number of resolutions. We consider a successful resolution, a resolution in which the relative error on voltage magnitude estimation is lower than 1%. For each configuration, the resolution has been launched 1,000 times without changing sensors locations and the operating point of the network. It is also necessary to know, that for each resolution, sensors can return different values because they are noisy.

Fig. 5 represents the performance evaluation realized on 64-buses network. We can see that with the configuration with two voltage sensors, the system has a performance really near to 100%. Based on what the state estimation is intended for, it may be not enough but we can see than with only three voltage sensors, the system is able to reach a performance of 100%. The results of this evaluation seem to indicate that this approach is valid and is suitable for distribution network.

B. Filtering Quality

Fig. 6 represents the number of occurrences of voltage magnitudes obtained for 5,000 resolutions on the 64-buses network for a given node. \( \mu \) represents the real voltage magnitude for this node. \( \sigma \) is the standard deviation of the voltage sensor present at this bus. \( \tau \) is the standard deviation of the results obtained thanks to the system. Table II presents the value corresponding to Fig. 6. We can see on this figure that the system effectively filters errors of the voltage sensor. The filtering of errors provided by the various sensors is a prerequisite of the state estimation. However, this study should be continued in this direction to filter even more the sensors data.

<table>
<thead>
<tr>
<th>TABLE II. MEASURED VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Time (in seconds)</td>
</tr>
<tr>
<td>Number of cycles</td>
</tr>
</tbody>
</table>

![Figure 5. Performance evaluation on a 64-bus distribution network](image)

![Figure 6. Gaussian distribution of a voltage sensor and the state estimation for a bus over multiple resolutions](image)
C. Computation Time

For this evaluation, we have measured the time and amount of cycles the system has to do to reach a valid solution. These measurements have been made on the state estimation of the 64-bus network launched 1,000 times. On the set of resolutions, we have decided to remove the ones in which the system was too close to the solution.

In order to regulate the voltage, it is mandatory for the system to respond in a minimum time. Indeed, in order to take a decision for voltage regulation, the state estimation must be as precise as possible. The state of a network is in constant evolution. Consequently, the more the system takes time to estimate the state, the more the estimation will be incorrect. Despite the fact that it highly depends on the performance of the computer the system runs on, these results are encouraging.

D. Test of the AMAS Theory

The AMAS theory considers that when all agents at the micro-level are in cooperative situations, the global system at the macro-level is functionally adequate (its gives correct results): this is its emergence property. For Atena, an agent estimates to be in a cooperative local situation when the Kirchhoff’s Current Law is verified. The global estimation is given by the state voltage estimation for each bus is close to its theoretical one. Fig. 7 gives these results for an Atena solving process on a given topology experiment. From evidence, the correlation between the micro and macro states assumed by AMAS theory is verified.

V. CONCLUSION AND PERSPECTIVES

We have determined that using an Adaptive Multi-Agent System is an interesting approach to make networks smarter. This system agentifies all buses of the electrical network as well as voltage sensors. The lines linking two buses are considered as resources. The solving process is strictly local and according to the cooperation process of the AMAS theory, this leads to satisfying results (Quality of results, Performance, Computation time ...)

Through this study, we have seen that using the Adaptive Multi-Agent System theory can be an interesting and innovative approach in term of performance and robustness.

From literature, we have observed that adapting techniques can be used for distribution systems. However, the performances are reduced and such a system is only able to estimate accurately some variables. Given these limitations, the state estimator produced can only handle the voltage regulation problem [15].

The error filtering realized by Atena is a first step toward a robust and efficient Distribution System State Estimation, however it is far less efficient than classical approaches derived from transmission network state estimation such as the one presented in [3].

These researches will be continued targeting a highest filtering of sensor data and giving the ability to the system to regulate the voltage of the network it is connected to.

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Energy Sustainability and Management of Data Center

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Abstract—The system reliability of Tier 4 or Class F4 or DC Category D can be derived by calculated probability density function (pdf), mean time between failures (MTBF), mean time to repair (MTTR), and failure rate (λ) of component statistical reliability, from IEEE 493, to availability of data center. Since, data center standards, Uptime Tier Classification, TIA-942, BICSI 002, BITKOM, and EN 50600, are defined system reliability design through topology. Most of topology defines by a single line diagram of power distribution systems (PDS). The PDS design approach is using a coherent zone protection mechanism. This mechanism is tried to get rid of single point of failure by applying redundant topology N, N+1, 2N, and 2(N+1) through PDSs. This paper describes the zone protection approach of system reliability design for Tier 4 data centers. This paper was conducted design analysis of power distribution systems (PDS) from 8 (Tier 3) data centers and 2 (Tier 4) data centers while compared 5 data center standards subject to how to build the highest reliability of data center through zone protection as a recheck point. The results of paper analysis propose zonal survivability stages by applying a concept of mission critical load shedding (MCLS).

Keywords—data center; system reliability; zone protection; power distribution; energy sustainability

I. INTRODUCTION

Electronic systems are designed to operate for specified period of time, which is determined by cost and performance, as well as customer requirements. The ability of electronic systems to operate within this time frame is referred to generally as reliability. Science power distribution systems (PDS) of data center consist of electronic components (devices), system reliability of PDS is robustly dependent on the reliability of the individual components in the sub-system environment. Presently, it is not feasible to predict the lifetime or degradation rate of any individual electronic component of PDS inside data center. It is possible to treat large populations of components and systems probabilistically and thereby predict average mean time to failure (MTTF). The results obtained from measuring and then predicting component survivability is used as input to a probabilistic analysis of the reliability of an entire data center system.

Power producers cannot guarantee an uninterrupted electrical power supply and in standard contracts, the power supply companies (PSCs) disclaim any liability. Short interruptions of longer power outages have therefore to be resolved by emergency power systems such as power generators and uninterruptible power supply (UPS) to ensure the continued operation of data centers with all their related technical systems such as climate control, power load, and security.

Statistical measures of data center system reliability, based on such probabilistic analyses, from the basis of engineering decisions. The available reliability tools permit the systems designer to secure, in general, system reliability from IEEE 493 Std. Design of Reliable Industrial and Commercial Power Systems [1] and BITKOM [8]. Consequently, an understanding of reliability at the component and sub-system level is essential to develop accurate estimates of data center system reliability.

This paper was conducted in-depth studies of existing work of power distribution system (PDS) design in data centers, and organized the PDS designs using a coherent zone protection approach. While there are many PDS designs for different components and systems of data centers, the PDS designs are largely unorganized, and lack an overall framework that allows data center designers to be used as a guideline to model more sophisticated and complex systems. Furthermore, this paper gave a more detailed taxonomy of the zone protection of system reliability design for data centers to understand the complexities of power distribution system in data center system architecture.

II. BACKGROUND

A. Data Center Standards

The Thai Government notes that there are multiple building standards governing data centre construction, including the Building Code of Thailand, and various local government Acts and regulations. It is expected that all proposed data centre facilities have, or will have, received all relevant and necessary approvals. As a basis for shared understanding, this paper nominates international standards such as Uptime [6], BICSI [7], TIA-942 [11], BITKOM [10], and EN 50600 [12], as mean of describing data center facilities, as presented in Figure 1.

Readers should note that rigid compliance with those international standards (Uptime as shown in Fig. 2; BITKOM as shown in Fig. 3; and BICSI 002 as shown in Table I) is not sought, as it is incompatible with some Thailand standards and local codes. The Thai Government also notes the technical guidance of the American Society of Heating, Refrigeration
and Air-conditioning Engineers (ASHRAE) [9] is also referenced widely. The ASHRAE guidance on achieving greater operational efficiency is of interest, but is not part of the formal requirements in this paper.

Solution. The expected number of failures between times \( t_1 \) and \( t_2 \) is given by multiplying the cumulative distribution function by \( n \) [2], the number of units:

\[
\bar{N} = n \left[ 1 - e^{-\int_{t_1}^{t_2} \lambda(t) \, dt} \right]
\]  

### Table I. BICS 002 Data Center Class

<table>
<thead>
<tr>
<th>System/Class</th>
<th>Class F0</th>
<th>Class F1</th>
<th>Class F2</th>
<th>Class F3</th>
<th>Class F4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Single path without any one of the following alternatives: power source, UPS, proper IT Grounding</td>
<td>Redundant, component-wise single path</td>
<td>Concurrently maintainable and portable</td>
<td>Fault tolerant</td>
<td></td>
</tr>
<tr>
<td>Utility</td>
<td>Single feed</td>
<td>Single feed</td>
<td>Single feed, source with 2 inputs of 1 source with single input electrically diverse from back-up generator</td>
<td>Dual feed from different utility substations</td>
<td></td>
</tr>
<tr>
<td>Topology</td>
<td>N or ( N+1 )</td>
<td>( N+1 )</td>
<td>Greater than ( N+1 )</td>
<td>( N+1 )</td>
<td></td>
</tr>
<tr>
<td>Redundancy</td>
<td>No requirement</td>
<td>( N+1 )</td>
<td>( N+1 )</td>
<td>( N+1 )</td>
<td></td>
</tr>
<tr>
<td>Generator run time</td>
<td>No requirement</td>
<td>8 hrs</td>
<td>24 hrs</td>
<td>72 hrs</td>
<td>96 hrs</td>
</tr>
<tr>
<td>Impact of downtime</td>
<td>Sub-local</td>
<td>Local</td>
<td>Regional</td>
<td>Multi-regional</td>
<td>Enterprise-wide</td>
</tr>
<tr>
<td>Annual allowable planned maintenance (hours)</td>
<td>12 hrs</td>
<td>24 hrs</td>
<td>72 hrs</td>
<td>96 hrs</td>
<td>144 hrs</td>
</tr>
</tbody>
</table>

### C. Data Center Topology

The quantification of the reliability of parallel units is based on the assumption that, when a redundant unit fails, the failure rate or the reliability of the surviving units does not change during the operating mission [14]. For example, in Fig 4, if \( N=1 \) topology: \( N=1 \) means a unit will take load at 100%; \( N+1 \) topology: \( N = 1 \) means 2 parallel units will take load at 100% each; \( N+1 \) topology: \( N = 2 \) means 3 parallel units will take load at 50% each.

There will be situations, however, when this will not prevail and the failure rate, or the reliability, of the surviving equipment will change. Usually their failure rate will increase and their reliability will decrease, because the surviving equipment will be sharing the load during the operating transfer mission; consequently, their share of the load will increase [13], as indicated in Figure 5.
The probability density function (pdf) of two parallel systems (N+1) [3], that two systems are equal (Note: N=1), when \( \lambda_1 = \lambda_2 = \lambda_3 \) is given by (1):

\[
R_{LS_1}(t) = e^{-2\lambda t} + \frac{2\lambda e^{-2\lambda t}}{2e^{-\lambda t} - e^{-2\lambda t}}
\]

(2)

\[f(T) = \lambda e^{\lambda t} - (\lambda_1 + \lambda_2)e^{\lambda_1 t} - (\lambda_2 + \lambda_3)e^{\lambda_2 t} - (\lambda_1 + \lambda_3)e^{\lambda_3 t}
\]

The topology of Tier 4 [6] or Class F4 [7] or DC Category D [10] is combination of (N+1) and 2(N+1) as illustrated in Fig. 6.

### III. RESEARCH METHODOLOGY

System protection is the art and science of detecting problems with power system components and isolating these components. Problems on the power systems are included, short circuits, abnormal conditions, and equipment failures.

This research question is what maximum IT downtime can the business tolerate? Which downtime of business on this paper was referred to power outages inside data centers, normally means all causes that happen from failures of parts, components, equipment, sub-systems, and systems. The power distribution analysis of data center was investigated by applying a research framework of reliability system which consisted of dependability and security system, as demonstrated in Fig. 7. This paper was conducted design analysis of power distribution systems (PDS) from 8 (Tier 3) data centers (6 sites are already on operations and the other 2 sites are under construction) and 2 (Tier 4) data centers (both site are under construction) in Thailand.

**Fig. 6.** Tier 4/Class F4/DC Category D 2(N+1) topology [15].

**Fig. 7.** Research framework of system reliability design for data center.

### IV. ZONE ANALYSIS OF POWER DISTRIBUTION SYSTEMS

The primary purpose of zone protection of PDS for data centers is to protect the mission critical equipment from out-zone faults (such as utility outage, transformer failure, generator malfunction, or battery failure: upstream loads) and in-zone faults (such as cables, breakers, distribution panels, and power supply units: downstream loads). Researcher was segregated PDS of data center into 5 zones: Zone 0, Zone I, Zone II, Zone III, and Zone IV, as presented in Fig. 8. Each zone needs to support power throughout other zone from Zone 0 till Zone IV. Dependability and security protection approach were analyzed through single line diagram of PDS in Fig. 8 and Fig. 9 respectively.

Dependability protection approach is considered redundant mechanism such as N+1, 2N, 2(N+1) topology. These scenarios are designed to get rid of single points of failure (SPOF) from PDS. As in Fig. 8, critical components are...
utilized to increase system reliability such as 2N utility sources, 2N transformers, (2N+1) power generators, 2N ATSs, and 2N PDSs through critical IT loads. This system protect approach is well-known in term of fault-tolerant which applies by all international data center standards such as Tier 4 [6], Class F4 [7], or DC Category D [10].

Security protection approach is derived from series system of security protection theory from (1). Security protection is reversed analysis from critical IT loads by applied mission critical load shedding (MCLS) called “zonal survivability” or Zone IV. An in-zone PDS may or may not need an energy storage module (ESM) to meet business downtime tolerance or quality of service requirements. ESM can use a host of technologies depending on the power load and energy requirements such as batteries, capacitors, flywheels, or superconducting magnetic energy storage. The time domain of ESM to supply to critical IT loads depends on business downtime tolerance and technologies vary from 15 seconds to 30 minutes. Security zone protecting can be classified into 4 stages, as depicted in Fig. 9. Zonal survivability or Zone IV is protected by Zone III (UPS + Batteries or Flywheels: 15 seconds to 30 minutes) stage 1, Zone II (Power Generator 12-96 hours) stage 2, and Zone I (Dual feed from different utility substations) stage 3.

A. Zone 0: Utilities (2N) Protection Approach

Possible causes of power outages: technical faults in the power transmission, sub-station, power distribution, utility breaker, and drop fuses (Out of control).

Multiple utility sources are employed to increase reliability is whether the sources should be operated in parallel or should be isolated, with an automatic transfer control scheme to switch from a failed source to the alternate source. The degree of independence of the utility sources is also important to determining the available improvement in data center system reliability. Multiple utility distribution feeders should preferable come from different substations.

Dual utility sources are not required to meet criteria for any Tier. Loss of utilities is not considered a failure but is a normal operational condition for which the data center must be prepared [6]. However, BICSI 002 [7] Class F4 requires dual feed from different utility substations.

Fig. 9. Security protection approach.

Fig. 8. Dependability protection approach.
B. Zone I: Generators (N+1) Protection Approach

Possible causes of power outages: technical faults in the power distribution system such as cables, breakers, and distribution panels; faults in the backup power systems such as continuous power generators.

Continuous generators [4] are compulsory applied with switching equipment or automatic transfer switch (ATS) on their output to transfer loads from the normal power supply to the generator and back to the normal power supply when it is available and acceptable. The ATS typically contains all controls essential to sense loss of the normal power supply, to start the continuous generators, and transfer the power to the load from one source or the other, including all critical time delays. Reliability protection in continuous generator power can be enhanced by application of more than one generator (N+1)[1], as shown in Figure 10, especially where data center downtime is not acceptable and when the size and number of loads can be separated (2N) according to their criticality. Uptime [6]: Tier 4 requires 12 hours of onsite fuel storage for N capacity while BICSI 002 [7]: Class F4 still requires fuel run time minimum 96 hours for N+1 capacity and BITKOM [10] requires fuel reserve minimum 72 hours. Therefore, the engine-generator plant may be not the only source of power reliability.

C. Zone II: UPSs (2N+1) Protection Approach

Possible causes of power outages: technical faults in the power distribution system such as cables, breakers, and distribution panels; faults in the uninterruptible power sources (UPS systems) or battery packed.

The UPS systems provide facility the highest level of protection by isolating the electronic equipment from raw utility power. The system performs by converting power from AC to DC and then back to AC. This unit is the only UPS that provides power with zero transfer time to the battery, making it ideal for sensitive and mission-critical equipment such as servers, storages, and networks. Additional, and online, double conversion UPS has an internal static bypass, ensuring that if installed UPS experiences a catastrophic failure or requires maintenance, system may be able to keep critical loads online during repair or replacement [5], as illustrated in Figure 11.

D. Zone III: Dual Power Paths (2N) Protection Approach

Possible causes of power outages: technical faults in the power distribution system such as cables, breakers, and distribution panels.

Since, Tier 4 is provided dual power distribution paths to IT load. Therefore, all IT equipment shall be dual powered as defined by the Institute’s Fault Tolerant Power Compliance Specification, Version 2.0 and installed properly to be compatible with the topology of the site’s classification.

E. Zone IV: Load Shedding Protection Approach

Possible causes of power outages: technical faults in the power distribution system such as cables, breakers, and distribution panels; technical faults in power supply units, or equipment such as servers, storages, or networks.

Load shedding schemes can be deployed to control peak demand levels to ensure service continuity to critical loads. A further consideration is the load shedding control system that initiates the shutting down of business application must be planned according to applications, servers, storages, and networks priority ranking. The control system makes recommendations regarding what the lowest priority processes to shutdown and calculates the residual additional uptime available to the high priority processes or critical applications. The highest critical applications and support systems equipment must be listed and put into group operations that support power from UPS batteries, as depicted in Figure 9. This is the last scenario of zone protection from utility outage, backup generators failed and only UPS batteries perform.

V. DISCUSSION

A system reliability design of data center can be described into 3 stages as sources of power protection, as presented in Fig. 12.

Stage 1: At normal of data center operations, power utility sources are operating as primary power source for data center.

Stage 2: At utility outage condition, at short duration <0.5 millisecond to 15 second UPS with flywheel systems can handle critical IT loads, UPS with battery systems will take action to protect critical IT equipment after flywheel already discharged. The design capacity of batteries loads is depended on critical IT application and equipment needs. This important information must be given from IT team to data center consultant or design to predict critical loads.

Stage 3: During operation of Stage 2, if the power utilities still not recover on normal function, after generator control
systems detected utility outage within 15 seconds power standby system is already to take load from Stage 2.

the highest system reliability of data center classification. This paper was investigated power distribution systems (PDS) of Tier 4 data centers and revealed a zone protection approach of each stage. The most important zone protection called “zonal survivability” which is contained the critical IT load applications or equipment. The zone protection approach can be categorized into 5 zones; Zone 0, Utilities 2N protection; Zone I, Generators 2(N+1) protection; Zone II, UPSs 2(N+1) protection; Zone III, Dual Power Paths 2N; Zone IV, Load shedding protection.

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VI. CONCLUSION

System reliability of data center depends on the outset design of power distributions system of data center which interprets data and information from business requirements. The crucial factor that requires complying is international standards such as Uptime, TIA-942, ANSI/BICSI-002, BITKOM, ASHRAE, and EN 50600. These standards have design guidelines and best practices for complying as in this paper referred to Tier 4/Class F4/DC Category D that means

Fig. 12. Operation modes of power distribution systems.

The system reliability of Tier X or Class FX or DC Category X can be derived by using calculated probability density function (pdf), mean time between failures (MTBF), mean time to repair (MTTR), and failure rate (λ) of component statistical reliability to availability of data center. Since, probability density function (pdf) of system connectivity such as N=1: when (N=1) sum = 2 units, (N=2) sum = 3 units can be calculated from (2) and (3) respectively. As definition of availability is defined as the probability that the system is operating properly when it is requested for use. While, reliability represents the probability of components, parts and systems to perform their required functions for a desired period of time without failure in specified environments with a desired confidence, therefore availability is a function of reliability (MTBF) and function of maintainability (MTTR). Statistically valid component values are available at IEEE Std. 493 [1].
A Study of the Reliability and Validity of the First Arabic Learning Styles Instrument (ALSI)

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Abstract— Research on education has indicated that students have different abilities and needs. In other words, they tend to learn in different ways, these ways were called a learning style. Although the learning style in many developed countries has seen a significant amount of research [1, 2], unfortunately, in Arabic region this work is still in its infancy [3-5]. The literature review revealed that there is no any learning style instrument has been designed to be applied in Arabic region and cultures. This lack encouraged the researcher to design and develop the first Arabic learning style instrument (ALSI). This study was conducted based on data collected from 111 students across 3 faculties and 2 higher institutes (polytechnics) at Misratah city in Libya. This paper also analysis the psychometric properties of the new instrument. This includes internal reliability, test-retest reliability, factor analysis and content validity index.

Keywords- learning; style; reliability; validity; instrument.

I. INTRODUCTION

The developed instrument was designed by the author based on Alzain learning style model (Figure 1) to assess the students’ preferences on four preferences. This is for the purpose of helping students and teachers on how they can learn and teach best by assessing four different preferences of learning which are as following:

- Visual (get more from visual form of information such as charts, pictures and graphs)
- Verbal (get more from verbal form of information such as text and audios)
- Active (get more from doing things)
- Passive (get more from reflecting about things)

The developed instrument consists of sixteen items, each of which has four choices which correspond to the four learning modes. And respondents give priority levels from 0 (least important) to 3 (most important), for the respective choices. The respondents are also allowed to give the same priority level for different choices at the same time. This mechanism provides a solution for the problems that might be arise from dealing the dimensions of learning style as dichotomies (either/or) options. The highest score possible is 48 and each preference is divided into three equal categories, these are a mild preference (from 1 to 16), moderate (from 17 to 32) and pure (from 33 to 48).

II. METHODOLOGY

The methodology that applied in this research included the data collection procedures from the participants. Also, some data statistical analyses were conducted to investigate the psychometric properties of the new instrument. The preferred learning style of 111 students was measured by using the new instrument and then the results was analysed using SPSS statistical package version 22.
III. RESULTS

The results of the instrument were entered in SPSS software. Moreover, the variables of gender, years of computer use and age were entered to investigate the correlation among these variables and the learning style.

A. Sample characteristics

Table I and Table II presents some demographic description and descriptive statistics about the students who participated in the research.

TABLE I: SAMPLE DESCRIPTION

<table>
<thead>
<tr>
<th>GENDER</th>
<th>Frequency</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>81</td>
<td>73.0</td>
</tr>
<tr>
<td>Male</td>
<td>30</td>
<td>27.0</td>
</tr>
<tr>
<td>Total</td>
<td>111</td>
<td>100.0</td>
</tr>
</tbody>
</table>

B. The preferred learning style of students

By analyzing the instrument, different learning styles were found. Table III presents participants’ classification based on their preferred learning style.

TABLE III: PARTICIPANTS CLASSIFICATION

<table>
<thead>
<tr>
<th>Active-Passive dimension</th>
<th>Visual-Verbal dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>Visual</td>
</tr>
<tr>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Passive</td>
<td>Verbal</td>
</tr>
<tr>
<td>11%</td>
<td>10%</td>
</tr>
<tr>
<td>No Preference</td>
<td>No Preference</td>
</tr>
<tr>
<td>4%</td>
<td>5%</td>
</tr>
</tbody>
</table>

As mentioned earlier, in each preference the highest score possible is 48 and each preference is divided into three equal categories, these are a mild preference (from 1 to 16), moderate (from 17 to 32) and pure (from 33 to 48). Figure 2 presents the classification of participants for each scale based on these three categories.
B. Internal consistency reliability

When a new instrument is developed, the first and most important issue considered by the developers is its reliability. The reliability refers to the repeatability and internal consistency, while the repeatability can be tested by test-retest reliability; the internal consistency can be estimated by conducting the Cronbach’s Alpha [6, 7].

In order to check the internal consistency reliability of the new instrument, Cronbach alpha coefficient was computed for each scale. Table IV shows the values of Cronbach alpha which are obtained based on a sample of 111 students, all of these values meet the criterion of Tuckman and Harper [8], who considered that alpha of 0.5 or greater is an adequate for the instruments that measure the attitude or preference such as learning style.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Alpha value 16 items</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>0.678</td>
<td>33.41</td>
<td>6.707</td>
<td>111</td>
</tr>
<tr>
<td>Passive</td>
<td>0.591</td>
<td>22.91</td>
<td>6.418</td>
<td>111</td>
</tr>
<tr>
<td>Visual</td>
<td>0.711</td>
<td>32.14</td>
<td>7.054</td>
<td>111</td>
</tr>
<tr>
<td>Verbal</td>
<td>0.577</td>
<td>22.29</td>
<td>6.334</td>
<td>111</td>
</tr>
</tbody>
</table>

To investigate whether the reliability of the instrument was negatively affected by any item, a Classical item analysis was conducted. The output of this test shows the weakest item in each scale and the largest increase in reliability if this item deleted, these items written in a red bold format Table V.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Corrected Item-Total Correlation</th>
<th>Squared Multiple Correlation</th>
<th>Cronbach’s Alpha if Item Deleted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>Q1ACTIVE 0.373</td>
<td>0.311</td>
<td>0.654</td>
</tr>
<tr>
<td></td>
<td>Q2ACTIVE 0.238</td>
<td>0.288</td>
<td>0.669</td>
</tr>
<tr>
<td></td>
<td>Q3ACTIVE 0.266</td>
<td>0.215</td>
<td>0.665</td>
</tr>
<tr>
<td></td>
<td>Q4ACTIVE 0.252</td>
<td>0.242</td>
<td>0.667</td>
</tr>
<tr>
<td></td>
<td>Q5ACTIVE 0.179</td>
<td>0.162</td>
<td>0.678</td>
</tr>
<tr>
<td></td>
<td>Q6ACTIVE 0.140</td>
<td>0.204</td>
<td>0.682</td>
</tr>
<tr>
<td></td>
<td>Q7ACTIVE 0.300</td>
<td>0.223</td>
<td>0.661</td>
</tr>
<tr>
<td></td>
<td>Q8ACTIVE 0.316</td>
<td>0.327</td>
<td>0.659</td>
</tr>
<tr>
<td></td>
<td>Q9ACTIVE 0.075</td>
<td>0.187</td>
<td>0.098</td>
</tr>
<tr>
<td></td>
<td>Q10ACTIVE 0.114</td>
<td>0.253</td>
<td>0.685</td>
</tr>
<tr>
<td></td>
<td>Q11ACTIVE 0.433</td>
<td>0.374</td>
<td>0.652</td>
</tr>
<tr>
<td></td>
<td>Q12ACTIVE 0.390</td>
<td>0.416</td>
<td>0.650</td>
</tr>
<tr>
<td></td>
<td>Q13ACTIVE 0.353</td>
<td>0.321</td>
<td>0.654</td>
</tr>
<tr>
<td></td>
<td>Q14ACTIVE 0.473</td>
<td>0.333</td>
<td>0.641</td>
</tr>
<tr>
<td></td>
<td>Q15ACTIVE 0.235</td>
<td>0.237</td>
<td>0.671</td>
</tr>
<tr>
<td></td>
<td>Q16ACTIVE 0.491</td>
<td>0.397</td>
<td>0.639</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scale</th>
<th>Corrected Item-Total Correlation</th>
<th>Squared Multiple Correlation</th>
<th>Cronbach’s Alpha if Item Deleted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>Q1PASSIVE 0.324</td>
<td>0.159</td>
<td>0.556</td>
</tr>
<tr>
<td></td>
<td>Q2PASSIVE 0.012</td>
<td>0.131</td>
<td>0.605</td>
</tr>
<tr>
<td></td>
<td>Q3PASSIVE 0.204</td>
<td>0.209</td>
<td>0.577</td>
</tr>
<tr>
<td></td>
<td>Q4PASSIVE 0.299</td>
<td>0.246</td>
<td>0.561</td>
</tr>
<tr>
<td></td>
<td>Q5PASSIVE 0.210</td>
<td>0.364</td>
<td>0.644</td>
</tr>
<tr>
<td></td>
<td>Q6PASSIVE 0.335</td>
<td>0.270</td>
<td>0.553</td>
</tr>
<tr>
<td></td>
<td>Q7PASSIVE 0.140</td>
<td>0.138</td>
<td>0.588</td>
</tr>
<tr>
<td></td>
<td>Q8PASSIVE 0.098</td>
<td>0.173</td>
<td>0.595</td>
</tr>
<tr>
<td></td>
<td>Q9PASSIVE 0.200</td>
<td>0.271</td>
<td>0.578</td>
</tr>
<tr>
<td></td>
<td>Q10PASSIVE 0.349</td>
<td>0.309</td>
<td>0.554</td>
</tr>
<tr>
<td></td>
<td>Q11PASSIVE 0.377</td>
<td>0.266</td>
<td>0.549</td>
</tr>
<tr>
<td></td>
<td>Q12PASSIVE 0.297</td>
<td>0.256</td>
<td>0.562</td>
</tr>
<tr>
<td></td>
<td>Q13PASSIVE 0.421</td>
<td>0.395</td>
<td>0.537</td>
</tr>
<tr>
<td></td>
<td>Q14PASSIVE 0.277</td>
<td>0.262</td>
<td>0.566</td>
</tr>
<tr>
<td></td>
<td>Q15PASSIVE 0.151</td>
<td>0.227</td>
<td>0.587</td>
</tr>
<tr>
<td></td>
<td>Q16PASSIVE 0.287</td>
<td>0.331</td>
<td>0.564</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scale</th>
<th>Corrected Item-Total Correlation</th>
<th>Squared Multiple Correlation</th>
<th>Cronbach’s Alpha if Item Deleted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>Q1VISUAL 0.406</td>
<td>0.397</td>
<td>0.688</td>
</tr>
<tr>
<td></td>
<td>Q2VISUAL 0.296</td>
<td>0.165</td>
<td>0.699</td>
</tr>
<tr>
<td></td>
<td>Q3VISUAL 0.474</td>
<td>0.488</td>
<td>0.676</td>
</tr>
<tr>
<td></td>
<td>Q4VISUAL 0.367</td>
<td>0.196</td>
<td>0.691</td>
</tr>
<tr>
<td></td>
<td>Q5VISUAL 0.348</td>
<td>0.297</td>
<td>0.693</td>
</tr>
<tr>
<td></td>
<td>Q6VISUAL 0.190</td>
<td>0.237</td>
<td>0.709</td>
</tr>
<tr>
<td></td>
<td>Q7VISUAL 0.269</td>
<td>0.195</td>
<td>0.702</td>
</tr>
<tr>
<td></td>
<td>Q8VISUAL 0.170</td>
<td>0.186</td>
<td>0.711</td>
</tr>
<tr>
<td></td>
<td>Q9VISUAL 0.457</td>
<td>0.307</td>
<td>0.680</td>
</tr>
<tr>
<td></td>
<td>Q10VISUAL 0.400</td>
<td>0.338</td>
<td>0.691</td>
</tr>
<tr>
<td></td>
<td>Q11VISUAL 0.397</td>
<td>0.279</td>
<td>0.691</td>
</tr>
<tr>
<td></td>
<td>Q12VISUAL 0.234</td>
<td>0.241</td>
<td>0.705</td>
</tr>
<tr>
<td></td>
<td>Q13VISUAL 0.313</td>
<td>0.331</td>
<td>0.696</td>
</tr>
<tr>
<td></td>
<td>Q14VISUAL 0.270</td>
<td>0.323</td>
<td>0.702</td>
</tr>
<tr>
<td></td>
<td>Q15VISUAL 0.355</td>
<td>0.170</td>
<td>0.691</td>
</tr>
<tr>
<td></td>
<td>Q16VISUAL 0.054</td>
<td>0.175</td>
<td>0.724</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scale</th>
<th>Corrected Item-Total Correlation</th>
<th>Squared Multiple Correlation</th>
<th>Cronbach’s Alpha if Item Deleted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal</td>
<td>Q1VERBAL 0.233</td>
<td>0.255</td>
<td>0.557</td>
</tr>
<tr>
<td></td>
<td>Q2VERBAL 0.232</td>
<td>0.266</td>
<td>0.557</td>
</tr>
<tr>
<td></td>
<td>Q3VERBAL 0.151</td>
<td>0.206</td>
<td>0.572</td>
</tr>
<tr>
<td></td>
<td>Q4VERBAL 0.201</td>
<td>0.262</td>
<td>0.563</td>
</tr>
<tr>
<td></td>
<td>Q5VERBAL 0.316</td>
<td>0.228</td>
<td>0.542</td>
</tr>
<tr>
<td></td>
<td>Q6VERBAL 0.242</td>
<td>0.270</td>
<td>0.555</td>
</tr>
<tr>
<td></td>
<td>Q7VERBAL 0.148</td>
<td>0.390</td>
<td>0.573</td>
</tr>
<tr>
<td></td>
<td>Q8VERBAL 0.157</td>
<td>0.134</td>
<td>0.570</td>
</tr>
<tr>
<td></td>
<td>Q9VERBAL 0.267</td>
<td>0.286</td>
<td>0.551</td>
</tr>
<tr>
<td></td>
<td>Q10VERBAL 0.106</td>
<td>0.166</td>
<td>0.577</td>
</tr>
<tr>
<td></td>
<td>Q11VERBAL 0.386</td>
<td>0.237</td>
<td>0.533</td>
</tr>
<tr>
<td></td>
<td>Q12VERBAL 0.363</td>
<td>0.390</td>
<td>0.533</td>
</tr>
<tr>
<td></td>
<td>Q13VERBAL 0.175</td>
<td>0.221</td>
<td>0.567</td>
</tr>
<tr>
<td></td>
<td>Q14VERBAL 0.389</td>
<td>0.372</td>
<td>0.529</td>
</tr>
<tr>
<td></td>
<td>Q15VERBAL 0.003</td>
<td>0.159</td>
<td>0.596</td>
</tr>
<tr>
<td></td>
<td>Q16VERBAL 0.055</td>
<td>0.371</td>
<td>0.589</td>
</tr>
</tbody>
</table>
The effect of weakest items on the reliability was highlighted in Table VI, the greatest increase was in passive scale, from 0.591 to 0.644.

### TABLE VI: CRONBACH’S ALPHA IF WEAKEST ITEM DELETED FROM EACH SCALE

<table>
<thead>
<tr>
<th>Scale</th>
<th>Alpha Value 16 items</th>
<th>Alpha Value 15 items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>0.678</td>
<td>0.690</td>
</tr>
<tr>
<td>Passive</td>
<td>0.591</td>
<td>0.644</td>
</tr>
<tr>
<td>Visual</td>
<td>0.711</td>
<td>0.724</td>
</tr>
<tr>
<td>Verbal</td>
<td>0.577</td>
<td>0.596</td>
</tr>
</tbody>
</table>

The positive note that we should mention is, no item fell below the level of 0.10 in Squared Multiple Correlation, which means the items in each scale are strongly related. “The Squared Multiple Correlation is essentially the degree to which variance of the item score is accounted for by the scores for the other items in the scale” [9].

### C. Test-Retest Reliability

As mentioned earlier, the reliability refers to the consistency and repeatability. Normally, test-retest method used to test the stability of the instrument over time. This method assumes that if the same instrument is used with the same or similar sample of participants then the results should not be different [4, 6]. In this research, test-retest analysis test was conducted and the time lapse between the measurements was three weeks. Table VII shows the results of the t-test, as we can note the results reveal that there are no significant differences between the means of scores on the four scales of measurements (P. value in each scale is > 0.05). Consequently, the results of t-test provide an evidence of repeatability for the ALSI.

### D. Content Validity Index

Researchers often investigate the content validity of new instruments by computing the content validity index (CVI). This method provides an evidence of content validity based on content experts rating, to calculate (CVI) the relevance of each item to underlying construct should be evaluated by a number (from 3 to 10) of experts [10].

In order to investigate the content validity of ALSI, the instrument was checked by six experts in the subject area. To avoid the neutral opinion, four-point ordinal scale were used to evaluate the relevance of items to underlying construct (1=not relevant, 2=somewhere relevant, 3=quite relevant, 4=highly relevant), this scale was recommended by Davis [11]. Then item content validity index (I-CVI) was computed for each item. Polit and Beck [10] reported that I-CVI = the number of experts giving a rating of (quite relevant) or (highly relevant) divided by the total number of experts. Consequently, the average of overall scale (S-CVI/Ave) can be computed by the averaging the I-CVIS or averaging the proportion of items which are rated as a relevant across experts. Table VIII illustrates the ratings of 6 experts for a new instrument.

### TABLE VII: RESULTS OF T-TEST

<table>
<thead>
<tr>
<th>Style</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>T</th>
<th>(P. Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>60</td>
<td>31.9167</td>
<td>6.17346</td>
<td>0.864</td>
<td>0.458</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>30.8824</td>
<td>6.40827</td>
<td>0.862</td>
<td></td>
</tr>
<tr>
<td>Passive</td>
<td>60</td>
<td>22.9500</td>
<td>7.11748</td>
<td>0.071</td>
<td>0.095</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>22.8627</td>
<td>5.55345</td>
<td>0.072</td>
<td></td>
</tr>
<tr>
<td>Visual</td>
<td>60</td>
<td>32.6833</td>
<td>6.97572</td>
<td>0.873</td>
<td>0.644</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>31.5098</td>
<td>7.16205</td>
<td>0.871</td>
<td></td>
</tr>
<tr>
<td>Verbal</td>
<td>60</td>
<td>21.8167</td>
<td>6.10499</td>
<td>0.850</td>
<td>0.461</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>22.8431</td>
<td>6.61021</td>
<td>0.844</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE VIII: RESULTS OF RATING ON A 16-ITEMS SCALE BY SIX EXPERTS

<table>
<thead>
<tr>
<th>Item</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
<th>Number of Agreements</th>
<th>Item CVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>0.83</td>
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<td>4</td>
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<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
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<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>0.83</td>
</tr>
</tbody>
</table>

| | Mean items CVI | 0.95 |
| | PR | 1.00 | 0.69 | 1.00 | 1.00 | 1.00 | 0.95 |
| | Proportion | Mean expert | S-CVI/UA (Universal Agreement) | 0.69 |

E: Expert
PR - Proportion Relevant
Based on Table VIII, all six experts rated 11 items out of the 16 as a quiet or high relevant and that means 69 per cent of items were rated as a relevant. However, the rest of items (3, 12, 13, 15 and 16) which were ranked as not relevant, these items were varied for the six experts. For example, only one expert out of six rated these items as not relevant.

According to Lynn [12], the value of I-CVIs should be in the vicinity of 0.8 when the number of experts is 5 or more. As noted from Table VIII, all of the items meet this criterion. And these results provide an evidence of content validity for ALSI.

E. Factor analysis

For more investigation, factor analysis was performed. This method is a statistical test used for testing the relationships within a set of observed variables, consequently, minimize the number of these variables to a small set of components [13]. According to Zywno [6], there are two approaches to estimate the number of extracted factors using the factor analysis. The first approach is Kaiser-Gutman approach which ignores the factors that their Eigenvalues less than 1.0.

Another approach is a "scree plot" approach, this approach focuses on the area of the scree plot where the eigenvalues are smoothly decreased to the right and ignores the factors which coming beyond this area. While the first approach (Kaiser-Gutman) sometimes extracts too many factors, sometimes the number of extracted factors by the second approach (scree plot) are too few. For this reason, some researchers suggest that the important criterion that we have to consider is the percentage of total variance that explained by the extracted factors, those researchers state that 50 per cent of total variance is an adequate [13]. The corresponding scree plot is shown in Figure 3.

According to Kaiser-Gutman standard (Eigenvalues > 1.0), the number of extracted factors was equal to 22, accounting for 74.86 percent of the total variance. And the number of extracted factors using the scree plot approach was 10, accounting for 49.11 percent of the total variance.

![Scree Plot](image)

Figure 3: Scree plot for factor analysis on the Arabic version of the new instrument
A factor analysis test was conducted for many times. For each time, the results reveal that the visual scale maintained stable structure, all of the visual scale items consistently loading on a two factors. The results also reveal that the other scales were related to more than two factors. Table IX shows the results of the ten-factor solution.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Number of factors</th>
<th>Factor</th>
<th>Number of items in each factor</th>
<th>Number of items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>2</td>
<td>3, 9</td>
<td>12, 3, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>3</td>
<td>1, 4, 5</td>
<td>11, 12, 13, 14, 15, 16, 17, 18, 19</td>
<td>6</td>
</tr>
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<td></td>
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<tr>
<td>Verbal</td>
<td>3</td>
<td>2, 10</td>
<td>2, 3, 4, 5, 6, 9, 10, 11, 12, 13, 14, 15</td>
<td>12</td>
</tr>
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<td></td>
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<tr>
<td>Passive</td>
<td>4</td>
<td>6</td>
<td>2, 3, 4, 7, 8, 10, 15, 16, 17, 18, 19</td>
<td>7</td>
</tr>
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</tbody>
</table>

IV. CONCLUSIONS AND RECOMMENDATIONS.

Data collection instruments can significantly affect any research outcomes. Accordingly, the instruments that will be used to collect the data must be both valid and reliable. Therefore, to develop a new learning style instrument, a number of rigorous procedures are required to ensure the scale’s validity and reliability [10]. In this study, a set of well-known procedures were conducted such as Cronbach’s alpha, test-retest reliability, content validity index and factor analysis. The reliability test of the four scales of ALSI shows that the value of Cronbach alphas ranged from 0.577 to 0.711 and this is acceptable because it is greater than 0.5 [8]. Moreover, the classical item analysis revealed that the reliability of the scales can be enhanced by eliminating the weakest question in each scale, and the greatest improve occurring for the passive scale, which increased from 0.591 to 0.644. These results, as well as the results of test-retest reliability, provide an evidence of reliability for the new instrument. Furthermore, the results of content validity Index and factor analysis provided an evidence of content and construct validity for ALSI.

In conclusion, this study reveals that the new Arabic learning style instrument (ALSI) is a reliable and valid psychometric instrument to assess the learning styles of students in Arabic countries. However, more work on it is still required.

REFERENCES


Session 2: Sustainable Energy Technologies and Waste Management

The Production of Polyhydroxybutyrate from Liquid Stillage and Its Application
(Authors: Aophat Choonut, Tewan Yunu, Nisa Paichid, Kanokphorn Sangkharak)

Simulation of Diffuser Augmented Wind Turbine Performance
(Authors: Hossam M. Elbakry, Ahmed A.A. Attia, Osama Ezzat Abdelatif, M. S. Zahran)

Cogeneration and District Heating Networks Measures to Remove Institutional and Financial Barriers that Restrict their Joint Use in the EU-28
(Authors: Antonio Colmenar Santos, Enrique Rosales Asensio, Patricia Sánchez Sánchez, David Borge Diez)
The Production of Polyhydroxybutyrate from Liquid Stillage and Its Application

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Abstract—The liquid stillage contained reducing sugars (fructose and glucose) and volatile fatty acids including acetic acid, propionic acid and butyric acid. 0.5 g/L of reducing sugar was found in raw stillage. Thereafter, ethanol was harvested and the stillage after ethanol recovery was utilized for polyhydroxybutyrate (PHB) production. The effect of stillage concentration, nitrogen source, temperature, agitation speed and initial pH were studied. The optimum condition for PHB production containing 50% of stillage with 5 g/L yeast extract as nitrogen source. The cultivation was incubated at 30° C under the agitation speed of 150 rpm and pH 7. The highest biomass (10.50±0.141 g/L) and PHB (5.75 g/L, 86.50±6.236% of dry cell weight, DCW) were obtained under optimum conditions. The PHB was further utilized for hydroxybutyrate methyl ester (HBME) production. The partial properties of HBME were studied.

Keywords— methyl ester; polyhydroxyalkanoates; polyhydroxybutyrate; PHAs; PHB; stillage

I. INTRODUCTION

Polyhydroxybutyrate (PHB) is an interesting value-added biomaterial that can be obtained by microorganisms from diverse carbon sources such as hydrolyzed polysaccharides (e.g. starch, cellulose), volatile fatty acids (e.g. butyric acid). There are three main industrially used substrates such as sucrose, sugar and corn [1]. Development of PHA as potential substitute material to some conventional plastics has drawn much attention due to the biodegradable and biocompatible properties of PHB. Although the large scale production of PHB is still under development, the production cost of PHA has been a major drawback. Consequently, scientists have shown immense progress in searching for low-cost substrates to reduce the cost of production. In addition, the ongoing commercialization activities in several countries are expected to make PHA available for applications in various areas soon.

Bioethanol, as a clean and renewable fuel, is considered as a good alternative to replace petroleum oil, and its production has increased considerably in recent decades [2]. However, high amount of waste also generate from the process. The residue from this process, called stillage, contains non-fermentable solids and water. In addition, the stillage, waste from ethanol production, can be a serious source of water pollution. Since the bioethanol production technology available as of 2000 inevitably results in the production of 11.1 - 16.4 L of ethanol fermentation waste (i.e. ethanol stillage) for every 1 L of ethanol production, the total estimation of the production of ethanol stillage would be approx. 179.82 - 264.06 million kL in Brazil (2005), 172.05 - 252.65 million kL in USA (2005) and 66.6 - 97.8 million kL in Japan (2030). The stillage can also be a valuable resource from which to recover useful products such as fertilizer, animal feed, or methane gas. Selecting the most appropriate stillage management is a matter of trade-offs between energy, economic, and environmental considerations. One can understand that the studies on the utilization of ethanol stillage are urgently needed [12]. However, little data of the re-utilization of stillage for ethanol production has been reported. It have been reported that high amount of total sugar (17 g/L) were presented in the stillage. Therefore, the stillage has been suggested as a novel substrate for PHB production [3-4].

PHB has a wide range of potential applications because of its desired features such as biocompatibility, biodegradability and negligible cytotoxicity to the cells. Hence, the potential application of PHB as replacement for petrochemical based polymers is gaining popularity in various fields involving packaging, medical and coating materials. These desirable properties in compounding and blending have broadened their performances as potential end-use applications. However, the application of PHB for biofuel or biofuel additive has only a little report. Therefore, the objectives of this study aim to understand that the studies on the utilization of ethanol stillage for biofuel production was also determined.
II. MATERIALS AND METHOD

2.1 Strain and medium

*Alcaligenes eutrophus* was obtained from the Thailand Institute of Scientific and Technology Research (TISTR) and used throughout this study. The culture of *A. eutrophus* was maintained on Luria-Bertani (LB) agar (peptone 0.5%, beef extract 0.3% and agar 1.5%). The inoculum was prepared by growing the cell in 25 mL of the sterile liquid medium in 100 mL conical flask on a rotary shaker (100 rpm) for 48 h [5].

2.2 The characterisation of stillage

The liquid stillage was obtained from Beverage mill (Thailand). The liquid stillage was collected and determined for total solids (TS), volatile solids (VS), total soluble solids (TSS) and chemical oxygen demand (COD) contents. All parameters were measured according to the APHA standard methods for the examination of water and wastewater [6].

The qualitative analysis of reducing sugars was analyzed by high-performance liquid chromatography, with Zorbax reverse-phase column and acetonitrile-H\(_2\)O as utilized as a mobile phase. However, volatile fatty acids were determined by a gas chromatography-Flame ionization detector with HP-1 column.

2.3 The production of polyhydroxybutyrate

*A. eutrophus* were cultivated and various parameters were determined including the effect of liquid stillage concentration (50-100%), effect of nitrogen source (yeast extract and peptone), effect of incubation temperature (28, 30 and 45°C) and effect of initial pH (4, 7 and 9). The samples were taken and characterized every 12 h up to 120 h.

2.4 The characterization of polyhydroxybutyrate

The PHB content and composition were determined by gas chromatography-mass spectrometry (GC-MS) and benzoic acid was used as the internal standard [7]. All data were calculated with the mean and standard derivation of three parallel studies.

2.5 Preparation of biofuel from polyhydroxyalkanoates

Hydroxybutyrate methyl ester (HBME) was produced via acid-catalysis. Acid-catalyzed hydrolysis of PHA was followed by Wang *et al.* [8] and Zhang *et al.* [9]. Purities of HAME were determined by GC equipped with a FID (Agilent 6890, U.S.A.) using benzoic acid as an internal standard [9, 10]. In addition, ATR-FTIR in the frequency range of 400-4000 cm\(^{-1}\) (Perkin Elmer) was used to investigate the chemical structures of HBME. Partial physical, chemical and fuel related properties of HBME were also determined in accordance with the ASTM standard. The fuel characterization was carried out in National Metal and Materials Technology Center (Thailand).

III. RESULTS AND DISCUSSION

3.1 The characterization of liquid stillage

Liquid stillage, a waste-effluent after ethanol, was first characterized. The liquid stillage was an acidic (pH 4.3-4.8).

The characteristic of liquid stillage after ethanol recovery was shown in Table 1.

Table I. THE CHARACTERISTIC OF LIQUID STILLAGE

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Liquid stillage (mg/L)</th>
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</thead>
<tbody>
<tr>
<td>Total solids (TS)</td>
<td>17,807</td>
</tr>
<tr>
<td>Volatile solids (VS)</td>
<td>14,400</td>
</tr>
<tr>
<td>Total soluble solids (TSS)</td>
<td>9.0</td>
</tr>
<tr>
<td>Chemical oxygen demand (COD)</td>
<td>20,900</td>
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</tbody>
</table>

Andalib *et al.* [10] also reported the characteristic of thin stillage from ethanol industry using corn as a substrate. However, the COD, TS, VS and TSS were 10-times higher than our study. The data indicated that the characteristic of stillage was dependent on substrate use for ethanol production. The sugar and volatile fatty acid contents in stillage were also determined. The stillage contained reducing sugars (fructose and glucose) and volatile fatty acids, including acetic acid, propionic acid and butyric acid. 1.48 mg/L of reducing sugar was found in raw liquid stillage. The presence of sugar and volatile fatty acid were analyzed by HPLC and GC. The presence of sugar and volatile fatty acid in stillage (this study) was similar to the sugar analysis of corn-ethanol stillage determined by Mitra *et al.* [11] and Eskicioglu *et al.* [12]. Therefore, the liquid stillage was suitable to utilize as a substrate for PHB production due to the presence of sugars and volatile acids.

3.2 The optimization on nutrient and environmental condition for PHB production using liquid stillage

3.2.1 The effect of liquid stillage concentration

Effect of liquid stillage concentration on growth and PHB production from *A. eutrophus* were studied where stillage concentration at 50 and 100%. The strain could grow on both concentration tested and using stillage at 50% gave the maximum cell growth PHB production (4.11±0.10 g/L and 88.38% of DCW) after 72 h cultivation.

3.2.2 The effect of nitrogen source

Sources of nitrogen included yeast extract and peptone at the concentrations of 5 g/L. The suitable nitrogen source was yeast extract with the optimal concentration at 5 g/L, as it gave the highest PHB concentration (5.75±0.11 g/L) and PHB content (86.50% of DCW). Nutrient limitation is necessary to trigger PHB accumulation, and generally ammonia is used as the critical control factor for uncoupling the growth of cells and PHB production. Maximum cell growth (8.04 g/L) and PHB content of the recombinant *E. coli* (30% of DCW) were obtained in the presence of yeast extract and peptone as nitrogen source with a combination of yeast extract and peptone gave higher PHB content (about 60% PHB of DCW) [13]. Similar results were obtained from cultivation of *Anaerobic succiniproducens* and *Phaffia rhodozyma* in the presence of yeast extract, and a combination of yeast extract and peptone [14, 15].

3.2.3 The effect of incubation temperature

Effect of incubation temperature on growth and PHB production from *A. eutrophus* were varied from 28, 30 and 45°C. The strain gave the maximum cell growth PHB...
production (5.75±0.10 g/L and 86.50% of DCW) after 72 h cultivation at 30°C of incubation temperature.

3.2.4 The effect of initial pH

A. eutrophus was cultivated in the optimal medium consisting of 50% stillage, 5 g/L yeast extract at 30°C. Effect of initial pH on the PHB production was investigated by adjusting the pH of the optimal culture medium at 4, 7 and 9. It was indicated that the highest productivity of PHB (5.75±0.20 g/L as well as the content of 86.50% of DCW) were achieved at pH 7.0 followed by the production of PHB obtained at pH 9 and 4, respectively. The significant effect of pH on PHB accumulation during batch experiments was therefore highlighted. The optimum pH at 7.0 was comparable to the pH around 6.5 for A. latus [16] as well as a suitable pH range of 6-7 for microbial growth [17]. In addition, depression of PHA production was profound at pH ≤7 as PHA content of R. spheroides RV was higher at pH 8.0 and 8.5 than that at pH 7.0 and 7.5 [18].

To specifically determined the composition of the synthesized PHB, the freeze dried cell material and commercial P(3HB) were subjected to esterification. The propyl esters formed were analyzed by gas chromatography and benzoic acid propyl ester was used as the internal standard. The peak corresponding to propyl ester of 3-hydroxybutyric acid was observed in the gas chromatogram for PHB from A. eutrophus. This indicated that the PHB accumulated by A. eutrophus using stillage as carbon source was polyhydroxybutyrate (PHB).

3.3 Time course on PHB production under optimal condition

A. eutrophus was cultivated in the optimal medium, pH was controlled at 7.0 and incubation at 30°C for 96 h. The cultivation was performed in a 5-L fermentor with aeration rate of 1.0 vvm and agitation speed of 150 rpm. The results were given in Figure 1.

![Figure 1. PHB concentration (▲, g/L) and PHB content (■, %) of A. eutrophus on optimal medium contained 50% stillage, 5 g/L yeast extract at 30°C under initial pH at 7.](image)

3.4 The production and characterization of hydroxybutyrate methyl ester

PHB from A. eutrophus was subjected to produce biofuel via acid-catalysis. Hydroxybutyrate methyl ester (HBME) was obtained from acid- and alkali-catalyzed hydrolysis of PHB with recovery yield at 80%. The recovery yield was determined with the ratio of recovered HBME to the original PHB. The purity of HBME was detected with GC equipped with FID. The purities of HBME from acid catalytic processes were above 95%.

A chemical formula and molar mass of HBME are C13H22O3 and 118 g, respectively. High carbon and oxygen content of HBME were observed at 85%wt and 41% wt, respectively. The density of HBME was 0.9 g/cm³ and the flash point of HBME was 66.4–68.5°C. High boiling point (150–152°C) and freezing point (-40°C) was observed in HBME. This revealed that HBME is safe when stored under room temperature and suitable for land transportation. However, low amount of the ignition point (80°C), octane (62.2) and cetane number (<1) was determined in HBME.

Table II. THE PARTIAL CHARACTERISTIC OF HYDROXYBUTYRATE METHYL ESTER

<table>
<thead>
<tr>
<th>Fuel properties</th>
<th>Unit</th>
<th>HBME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td></td>
<td>C13H22O3</td>
</tr>
<tr>
<td>Molar mass</td>
<td>g</td>
<td>118</td>
</tr>
<tr>
<td>Carbon content</td>
<td>% wt</td>
<td>85</td>
</tr>
<tr>
<td>Oxygen content</td>
<td>% wt</td>
<td>41</td>
</tr>
<tr>
<td>Density (20°C)</td>
<td>g/cm³</td>
<td>0.9</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
<td>68.5</td>
</tr>
<tr>
<td>Ignition point</td>
<td>°C</td>
<td>80</td>
</tr>
<tr>
<td>Boiling point</td>
<td>°C</td>
<td>150</td>
</tr>
<tr>
<td>Freezing point</td>
<td>°C</td>
<td>-40</td>
</tr>
<tr>
<td>Octane number (RON)</td>
<td></td>
<td>62.2</td>
</tr>
<tr>
<td>Cetane number</td>
<td></td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

CONCLUSION

The polyhydroxybutyrate production from liquid stillage are optimized under the condition consisting of 50% stillage concentrations, 5 g/L of yeast extract of nitrogen sources, at 30°C and pH 7 which obtained the highest PHB of 86.50 % of DCW. The PHB was further utilized for hydroxybutyrate methyl ester (HBME) production using acid catalysis. The partial properties of HBME was studied. High HBME recovery percentage and purity were obtained. High molar mass, density, carbon and oxygen content, boiling point and freezing point of HBME revealed the possible ability to utilize HBME as novel biofuel or fuel additive.

ACKNOWLEDGMENT

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REFERENCES


Abstract - The main objective of this research is to optimize the diffuser design of Diffuser Augmented Wind Turbine (DAWT). Specifically, this study investigates the effect of different shapes of diffusers to develop the suitable diffuser parameter for the wind turbine power enhancement. For that purpose, two diffuser cases have been recommended as an effective design in increasing wind speed, using a validated model of a small commercial wind turbine (AMPAIR-300) in it were developed and each case is simulated and analyzed using design software Solid-works and Computational Fluid Dynamic (CFD) software Fluent-ANSYS-15. As per the study, for diffuser case-1, the diffuser splitter degrades the diffuser effect when its open angle higher than the diffuser open angle, for diffuser case-2 the diffuser splitter enhance the diffuser effect when its open angle lower than diffuser open angle, also adding inlet shroud directs the wind flow into the inlet of diffuser and the diffuser flange effect on the power enhancement was significant and also its induced axial load was significant, and it is recommended to study the optimum dimension of inlet shroud, diffuser flange and diffuser splitter to minimize the coefficient of thrust and to enhance the coefficient of power.

Keywords: Wind Power, CFD, Augmented diffuser wind turbine

I. INTRODUCTION

Wind energy technologies have become one of the fastest growing energy sources in the world and it symbolize a virtual endless resource, however, in comparison with the growing worldwide energy demand, the scale of wind energy is still very meager, as for many causes including cost [1], [2].

Diffuser augmented wind turbine (DAMWT) have been an exciting topic in wind energy technologies since 1979, its ideology is to increase the extracted power by increasing the mass flow through the rotor. Diffuser generated a sub-atmospheric region at its outlet, which appears to draw more wind through the rotor compared to a bare turbine, a slight increase in wind speed can result in a large increase in power output, since wind power generation is proportional to the cube of the wind speed, Diffuser augmented wind turbines have been investigated for more than fifty years as a remedy in wind industry [3].

They showed that the speed-up is not only influenced by the thrust coefficient but by three other coefficients namely: shroud inlet efficiency, pressure recovery coefficient, and base pressure coefficient, all of which can be related to the shroud shape and geometry [4], [5].

They studied the power augmentation of a small wind turbine (AMPAIR-300) shrouded with a simple frustum diffuser, based on diffuser length and area ratio (outlet area/inlet area) using 3D-CFD simulations, and stated that viscous loss in the inlet is negligible and flow separation in the diffuser leads to a significant performance loss, and proposed a well-designed duct as a flanged diffuser that creates a large base pressure [6], [7].

They developed the Vortec-7 DWT where multi-slotted diffuser to prevent separation was used, which has been unsuccessful, because of the immense loading on the duct in storm conditions or in yawed flows. Also they demonstrated that the power augmentation provided by a duct could be obtained at lower cost by extending the rotor diameter. Which have been modeled at flow speed of 1 m/s, an extended blade with diameter equal to the diameter of shroud exit generates the same power as the shrouded turbine [8], [6], [1].

Using CFD investigated the effect of adding flange at the diffuser exit plane, examined the optimal form of the flanged diffuser, and demonstrated that power augmentation by a factor of about four to five, as the base pressure at the exit plane can be lowered further due to the vortex formation at the outlet plane, the pressure down-stream of the flanged diffuser turbine will be lower and hence greater flow rate is drawn into the rotor [9], [10].

They investigated the effect of diffuser with airfoil (NACA0015) cross section geometrical features, using CFD, to find the influence of shroud geometrical features and found that flow separation of diffuser wall and base pressure coefficient is the most influential parameter in $C_p$, while inlet efficiency has only small impact [11].

Throughout the development of diffusers for a Diffuser Augmented Wind Turbine (DAWT), computational modeling has proved to be a valuable tool. It has been used to interpret full-scale field results from the Vortec 7 prototype DAWT, in an effort to find a diffuser design which is both aerodynamically efficient and can be manufactured at a reasonable cost [13].

The research presented in this paper parameterizes the power augmentation of a validated model of a small wind turbine (AMPAIR-300) shrouded with a simple frustum diffuser, the results of bare turbine simulations are compared with experimental data from the wind turbine manufacturer and [11]. This study aims to validate and analyze the two diffuser cases mentioned in Table 1, recommended from [2] as an effective design in increasing wind speed and it is recommended to consider momentum transfer to the turbine blade to be optimized in terms of wind turbine (AMPAIR-300) power coefficients.

The diffuser parameter dimensions mentioned in Table 1 and Fig. 1. As the diffuser length presented in by Ref.[2] equals to 250% of turbine rotor, which cannot be feasible to apply in simulation because of high no. of mesh elements.
required, then, the diffuser length presented in this paper ranged from 15% to 40% of turbine rotor diameter as presented in by [11] to mention the effect of increasing the diffuser length for both cases up to the length presented by [2], and to minimize the diffuser loads.

The diffuser case-1 have been used to study and validate the effect of adding a diffuser splitter with open angle higher than diffuser open angle at turbine downstream, and a comparison of power, axial force, velocity vectors and contours between diffuser case-1 and a diffuser with the same open angle but without diffuser splitter.

The diffuser case-2 have been used to study and validate the effect of adding a diffuser splitter with open angle lower than diffuser open angle, inlet shroud and diffuser flange, a comparison of power, axial force, velocity vectors and contours between diffuser case-2 and a diffuser with the same open angle but without "diffuser splitter, inlet shroud and diffuser flange".

II. MODEL DESCRIPTION

A. Diffuser Geometry

The commercial small wind turbine selected for simulation and validation was AMPAIR 300-Watt micro-wind turbine, (Ampair.com2013). The rotor radius is 600 mm as mentioned in manufacturer manual.

Fig. 1 shows the parameters of the diffuser augmented wind turbine, its length shown by L, the difference between inlet and outlet radius of the diffuser shown by Diffuser open angle "α", diffuser splitter length shown by LD, its inlet radius shown by Di , its splitter open angle α, inlet shroud with radius R1, and a flange at the diffuser outlet with height H1, the validated model turbine shrouded with each diffuser case have been placed in an enclosure of 5 meter radius and placed at 2 meter from inlet of 10 meter length of enclosure "outer cylinder".

<table>
<thead>
<tr>
<th>Diffuser cases</th>
<th>A</th>
<th>α1</th>
<th>LD</th>
<th>D1</th>
<th>H1</th>
<th>R1</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-1 (concept-2 presented by Reference [2])</td>
<td>4°</td>
<td>8°</td>
<td>0.5L</td>
<td>0.5D</td>
<td>-</td>
<td>-</td>
<td>0.15D</td>
</tr>
<tr>
<td>Case-2 (concept-4 redeveloped by Reference [2])</td>
<td>16°</td>
<td>4°</td>
<td>0.5L</td>
<td>0.5D</td>
<td>0.5R</td>
<td>0.1R</td>
<td>0.15D</td>
</tr>
</tbody>
</table>

Table 1: The dimensions of the recommended model cases

The diffuser was modeled with wind turbine inside it, using two diffuser cases (concept 2 and redeveloped concept no. 4) named and mentioned by [2], summarized in table 1, the distance between the rotor blade tip and the inner surface of diffuser "tip clearance" equals to one percent of turbine radius "R" as presented by [1]. The wall thickness of diffuser, splitter, inlet shroud curvature and diffuser flange equals to one percent of turbine rotor diameter, presented by [1].

The two diffuser cases have been simulated in two diffuser length with maximum length equal to 40% of turbine diameter and minimum length equals to 15% of turbine diameter to reduce the no. of mesh elements required for simulation which explained in MESH and Boundary Conditions.

The virtual shrouded turbine was simulated with rotor rpm between 150 rpm and 1377 rpm with increment of 153 rpm (λ=1). While wind speed was constantly 10ms⁻¹, thus variations of λ (tip speed ratio) was achieved by varying rpm at the chosen wind speeds. The axial force exerted on the DAMWT can be calculated directly from the pressure on the blade surface, but the power captured by the turbine should be calculated by multiplying T (the torque on the DAMWT rotor) by the (rotor rotational velocity).

\[ \lambda = \frac{\omega R}{U} \]  

Where \( \lambda \) is tip speed ratio, \( \omega \) is rotational speed of rotor, R is rotor radius, and U is wind speed.

The CFD software calculates the torque directly. In the case of bare turbine the area is the turbine swept area whilst in the case of diffuser augmented turbine the area is the diffuser outlet area, which the \( C_p \) (power coefficient) and \( C_{f} \) (thrust coefficient) of the DAMWT to be calculated from the following equations:

\[ C_p = \frac{P_{calculated}}{P_{wind}} = T/\left(0.5 \rho U^2((\pi(D/2) + H)^2)\right) \]  

Where \( C_p \) is coefficient of power, \( P_{calculated} \) is extracted power from rotor, \( P_{wind} \) is ideal extracted power of wind, D is rotor diameter, T is torque exerted on the rotor, \( \rho \) is air density, and \( H \) is difference between inlet and outlet radius of the diffuser.

\[ C_f = \frac{F_{measured}}{F_{wind}} = F/\left(0.5 \rho U^2((\pi(D/2) + H)^2)\right) \]  

Where \( C_f \) is coefficient of thrust, \( F_{measured} \) is total axial thrust force on rotor, and \( F_{wind} \) is ideal axial thrust force on rotor.

Selection of an appropriate model for CFD simulation because not every model can predict precisely separation phenomenon [14]. While separation from diffuser surface greatly affects the performance of the diffuser, SST model has been validated extensively for separating 2D flows with Reynolds-averaged-Navier–Stokes (RANS) models. Reference [6] showed the SST model outperformed the 4-equation, \( \nu^2 - f \) (transition SST) model in predicting separating velocity profiles for the NACA 4412 airfoil case and suggested that flow over the rotor blades can be subject to significant region of laminar turbulence transition and because the transition process can affect the separation behavior of the boundary layer on the blade surface. It is agreed that the \( \nu^2 - f \) model is the best model in case of separation [16].

This model is a modified SST \( k-\omega \) RANS turbulence model by the addition of two other transport equations for \( \gamma \) (the intermittency) and the transition onset criteria.

The transition SST model constants were kept as its default with following values: \( \text{Alpha}^+_{inf}=1, \text{Alpha}_{inf}=0.52, \), \( \text{Alpha}_0=0.111, \text{Beta}^+_{inf}=0.09, a_1=0.31, \text{Beta}_1 \) (Inner)= 0.075, \( \text{Beta}_i \) (Outer)= 0.0828, \( \text{Cai}=2, \text{Ca2}=0.06, \text{Ce1}=1, \text{Ce2}=50, \text{C_thetat}=0.03, \text{C_s1}=2, \text{TKE}(\text{Inner})\text{Prandtl}=1.176, \text{TK}
Ansys Fluent was used to create the model and mesh in this study, in order to validate accurately with the commercial wind turbine "AMPAIR-300".

Given the common use of commercial wind turbine "AMPAIR-300" from [7], the coefficient of power $C_p$ of the present model have been compared with [7] model in tip speed ratio $\lambda$ from 1 to 9, and as mentioned in section 2.3, inlet velocity was 10ms$^{-1}$ and all the other boundary conditions were set for both cases.

As shown in Fig. 3, the optimum tip speed ratio for the present model $\lambda=6$, but for the [7] model $\lambda=3$ and the coefficient of power results are not the same and there is some difference between both model results, there is possible reasons for these differences. The 1$^{rd}$ reason: the rotor diameter equals 1.3m presented by [7], while at the present work, the rotor diameter equals "1.2m", while as mentioned in manufacturer manual [ampair-300.com] the rotor diameter equals to "1.2m" without blade curved tip exactly as the present model, and the curved tip equals to "60mm" for full rotor diameter, the 2$^{nd}$ reason: the difference in the type and size of meshing technique differ between both models, and the 3$^{rd}$ reason: the present work model used an airfoil profile NACA-4412 as the only airfoil profile for the turbine blade span, but [7] might use multiple airfoil profiles.

As shown in Fig. 4, the results have been validated mainly by power output reported from the manufacturer in different wind speeds. Hence bare turbine simulations have been done in wind speeds of (5, 7.5, 10, 12.5 and 15ms$^{-1}$). Power and rpm related to each wind speeds, are presented by the manufacturer of AMPAIR-300 turbine. Rpm of the turbine was 10ms$^{-1}$ and as mentioned in manufacturer manual [ampair-300.com] the rotor diameter equals to "1.2m", while [7] might use multiple airfoil profiles.

The results are so close and the difference between simulation and experimental results are acceptable because all the boundary conditions and coefficients in the simulations could not be set as in experimental test.

IV. RESULTS AND DISCUSSION

The amount of wind energy of the air passing the rotor area is proportional to its mass flow rate. There are some methods...
to increase this mass flow. One method is shrouding the rotor with a diffuser, and the other method is increasing the swept area of the rotor by enlarging its diameter.

Hence, using the diffuser is not desirable, unless its coefficient of power prove to be very economical, degree of flow separation from the diffuser surface, base pressure reduction at the diffuser exit (back pressure effect) mentioned

In the review as a significant parameter in diffuser performance. In this study power augmentations of the diffuser shrouded small turbines is parameterized by study and analyze diffuser cases presented in section "Model and Diffuser Geometry".

A. Diffuser Case -1

An increase of 35% of wind speed at diffuser inlet reported by [2] with diffuser length equals to 250% of diffuser inlet diameter, soPower extracted from a wind turbine can be achieved in different λ's, based on rotor operation, but there is an optimum point at which further increase in λ reduces output power.

In Fig. 5, as shown, coefficient of power of bare turbine and diffuser case-1 at both lengths (L/D=0.15), (L/D=0.4) versus tip speed ratio λ, also the coefficient of power at optimum tip speed ratio (λ=6) at diffuser (without splitter) in both lengths (L/D=0.15), (L/D=0.4).

In Fig. 5, as shown the optimum tip speed ratio pointed in circles decreased after using diffuser case-1, even lower than the bare turbine, but increasing the diffuser length to (L/D=0.4), leads to an increase in power extracted, and this validate the effect of diffuser length in reducing the flow separation and enhance the mass flow rate as mentioned in [7].

In Fig. 6, as shown the coefficient of thrust of the rotor of diffuser case-1 (L/D=0.4) and the total Cₜ of diffuser case-1 versus tips speed ratio λ, also the coefficient of thrust in percentage of rotor and total thrust at optimum (L/D=0.15) of the diffuser (without splitter).

In Fig. 6 as shown at λ=6 pointed with dashed rectangle line, comparing the total thrust of case-1 results and diffuser results, found that case-1 with higher thrust than diffuser, but the rotor thrust of case-1 at λ=6 is lower than rotor thrust of diffuser, which confirm the same effect on both diffuser lengths (L/D=0.15) and (L/D=0.4).

In Fig. 6 and Fig. 7 as shown at optimum tip speed ratio pointed with circles (λ=5) the total coefficient of thrust increased from 50% to 58% approx. when the diffuser length increased from L/D=0.15 to L/D=0.4 and this indicate that increasing the diffuser length up to (L/D=2.5) will increase the power extracted but also the viscous losses and axial loads on the structure support will be increased significantly.

In Fig. 8 and Fig. 9 it shows the velocity contour and vectors to present the flow profile including the separation region at turbine downstream in the area below the diffuser surface for the diffuser (without splitter) at diffuser length (L/D=0.15) and (L/D=0.4).

In Fig. 8 It shows due to the low diffuser open angle "4°", the low diffuser length (L/D=0.15), and the high velocity of flow at turbine blade tip , all these parameters avoids the formation of a zero speed area on the diffuser surface (boundary layer) on diffuser surface to draw more wind to enhance the mass flow rate.

In Fig. 9 It shows that increasing the diffuser length enhanced the formation of a zero speed area on the diffuser surface (boundary layer) which enhances the draw of more wind flow (mass flow rate).
Figure 5: Coefficient of power $C_p$ of present model results with diffuser case-1 results with diffuser (without splitter) at optimum tip speed ratio $\lambda (=6)$ results Versus Tip Speed Ratio $\lambda$ at wind speed of 10ms$^{-1}$.

Figure 6: Coefficient of Thrust (\%) of present model results with diffuser case-1 (at L/D=0.4) results with diffuser (without splitter) at optimum tip speed ratio $\lambda (=6)$ results Versus Tip Speed Ratio $\lambda$ at wind speed of 10ms$^{-1}$.

Figure 7: Coefficient of Thrust (\%) of present model results with diffuser case-1 (at L/D=0.15) results with diffuser (without splitter) at optimum tip speed ratio $\lambda (=6)$ results Versus Tip Speed Ratio $\lambda$ at wind speed of 10ms$^{-1}$.
In Fig. 10 and Fig. 11 it shows the velocity contour and vectors to present the flow profile including the separation region at turbine downstream in the area below the diffuser surface for the diffuser case-1 at diffuser length (L/D=0.15) and (L/D=0.4).

In Fig. 10 it shows that due to the low diffuser length, and the boundary layer associated with the splitter surface, an action of braking induced to the wind flow at turbine downstream, which reduced the diffuser effect of drawing more mass flow rate. Also, since the splitter open angle higher than diffuser open angle, the effect of nozzle induced in the area between the splitter surface and diffuser surface reduced the ability of boundary layer formation because of the wind velocity increased in this area more than that mentioned in Fig. 8.

Also, since the increasing of diffuser length decreased the effect of braking of wind flow at turbine downstream, the formation of nozzle effect directs the flow to the area below the splitter which reduces the diffuser effect and increases the splitter effect, which can be more effective with higher diffuser open angles.

### B. Diffuser Case-2

An increase of 61.25% of wind speed at diffuser inlet reported in [2] with diffuser length equals to 250% of diffuser inlet diameter and with diffuser flange height H_1/D=1 which both changed to (L/D=0.15), (L/D=0.14) and (H_1/D=0.25) to be applicable in simulation.

In Fig. 12 as shown, coefficient of power of bare turbine and diffuser case-2 at both lengths (L/D=0.15), (L/D=0.4) versus tip speed ratio λ also the coefficient of power at optimum tip speed ratio (λ=6) at diffuser (without splitter) in both lengths (L/D=0.15), (L/D=0.4).

In Fig. 12, as shown the optimum tip speed ratio pointed in circles increased after using diffuser case-2, it shows that using the splitter with open angle 4°, inlet shroud and diffuser flange. As shown the coefficient of power increased compared to the bare turbine about 70% using diffuser length L/D=0.15 and about 100% using diffuser length L/D=0.4 also the case-2 results higher than that of the diffuser with the same open angle about 50% using diffuser length L/D=0.15 and about 50% using diffuser length L/D=0.4 at optimum tip speed ratio λ=6 pointed in dashed rectangle.

In Fig. 13, shows the coefficient of thrust of the rotor of diffuser case-2 (L/D=0.4) and the total C_t of diffuser case-2 versus tips speed ratio λ, also the coefficient of thrust of rotor and total thrust at optimum λ(=6) of the diffuser (without splitter).

In Fig. 13 as shown at λ=6 pointed with dashed rectangle line, comparing the total thrust of case-2 results and diffuser results, found that case-2 (C_t=400%) with higher thrust than diffuser (C_t=110%) at λ=6, although case-2 coefficient of power higher that of diffuser just 50% , and also the rotor thrust of case-2 at λ=6 is higher than rotor thrust of diffuser but so close, and this indicate that the very high total thrust of case-2 requires special support structure, which affect the economic view of the diffuser case-2.
And since the diffuser splitter have a small effect on total thrust, then the diffuser flange and inlet shroud the main cause of the high increase of total thrust diffuser case-2.

In Fig. 14 as shown the coefficient of thrust of the rotor of diffuser case-2 (L/D=0.15) and the total Cₜ of diffuser case-2 versus tip speed ratio λ, also the coefficient of thrust of rotor and total thrust at optimum λ(=6) of the diffuser (without splitter).

In Fig. 14 as shown at λ=6 pointed with dashed rectangle line, comparing the total thrust of case-2 results and diffuser results, found that case-2 (320%) with higher thrust than diffuser (80%) at λ=6, and the rotor thrust of case-2 at λ=6 is higher than rotor thrust of diffuser, which indicate that the coefficient of power increases 50% as mentioned in Fig. 12, while the coefficient of thrust increases up to 320%. But comparing with case-2 (L/D=0.4), found that the coefficient of thrust decreases as the diffuser length decrease which indicate that the usage of diffuser case-2 should be with the minimum diffuser length to minimize the induced coefficient of thrust and then minimize the required structure support.

Figure 12: Coefficient of power Cₚ of present model results with diffuser case-2 results with diffuser (without splitter) at optimum tip speed ratio λ (=6) results Versus Tip Speed Ratio λ at wind speed of 10ms⁻¹

Figure 13: Coefficient of Thrust (%) of present model results with diffuser case-2 (at L/D=0.4) results with diffuser (without splitter) at optimum tip speed ratio λ (=6) results Versus Tip Speed Ratio λ at wind speed of 10ms⁻¹
In Fig. 15 and Fig. 16 it shows the velocity contour and vectors to present the flow profile including the separation region at turbine downstream in the area below the diffuser surface for the diffuser (without splitter) at diffuser length (L/D=0.4) and (L/D=0.15).

In Fig. 15 it shows that increasing the diffuser length and open angle enhanced the formation of a zero speed area on the diffuser surface (boundary layer) which enhances the draw of more wind flow as mentioned in the velocity vectors and contours.

In Fig. 16 It shows due to the low diffuser length (L/D=0.15), and the high velocity of flow at turbine blade tip, all these parameters reduced the area of boundary layer on diffuser surface, but the high diffuser open angle assist the partly formation of the boundary layer and this indicates that as the diffuser open angle increases, as the effect of "high velocity wind flow at tip of the turbine blade" decreases, and this presented significantly that at low diffuser open angle as diffuser case-1 mentioned in Fig. 9 affects significantly the formation of the boundary layer.

In Fig. 17 and Fig. 18 it shows the velocity contour and vectors to present the flow profile including the separation region at turbine downstream in the area below the diffuser surface for the diffuser case-2 at diffuser length (L/D=0.15) and (L/D=0.4),and the flow profile effected by diffuser flange and inlet shroud.

In Fig. 17 it shows that the diffuser flange increased the layer of vortices behind the flange at the downstream of the diffuser and enhances the mass flow rate at turbine downstream.

As shown in Fig. 17 the inlet shroud directs the wind flow rate to the diffuser inlet and assist the formation of the boundary layer on outer surface of diffuser which directs the flow into the diffuser inlet and to the tip of the diffuser flange which assist the formation of vortices at diffuser downstream.

As shown in Fig. 17 Although the decrement effect on mass flow rate due to, the high speed wind flow at turbine blade tip which cause the deformation of boundary layer on
diffuser surface due to the low diffuser length, also the effect of the boundary layer associated with the splitter surface which cause an action of braking to the wind flow at turbine downstream. Also, the effect of nozzle induced in the area between the splitter surface and diffuser surface which affect the formation of boundary layer on the diffuser surface. This indicates that the inlet shroud and diffuser flange enhance the mass flow rate significantly, as its mass flow rate enhancement overcomes these decrement effects.

In Fig. 18 it shows that the increasing of diffuser length assist the inlet shroud to form a bigger boundary layer on the outer surface of the diffuser along the diffuser length which assist the formation of vortices behind the diffuser flange which enhance the mass flow rate.

In Fig. 18 it shows that increasing the diffuser splitter length assist the formation of a boundary layer which enhance the mass flow rate although the low splitter open angle.

V. CONCLUSION AND RECOMMENDATION

A model of AMPAIR-300 wind turbine was shrouded with two recommended diffuser cases in CFD simulations.

Diffuser case-1 used to study the effect of diffuser-splitter placed at turbine downstream and found that, at splitter angle higher than the diffuser angle the diffuser effect reduced due to the nozzle effect induced between the surfaces of splitter and diffuser which induce an act of braking effect on the upstream flow.

It is recommended studying the effect of various angles of diffuser with various angles of diffuser splitter to find the optimum angle of splitter and diffuser collection gives highest enhancement in power extracted.

Diffuser case-2 used to study the effect of diffuser-splitter with low open angle, inlet shroud and diffuser flange and found that, at splitter angle lower than the diffuser angle the diffuser effect enhanced due to the increase in mass flow rate showed in velocity vectors and contours induced between the surfaces of splitter and diffuser which induce a low pressure effect on the downstream flow, also the inlet shroud effect to direct the wind flow to the inlet of shrouded turbine and the diffuser flange effect of inducing vortices at diffuser downstream to increase the low pressure effect on downstream which enhance the mass flow rate.

Both diffuser cases validate the effect of diffuser length on mass flow rate enhancement with two diffuser lengths (L/D=0.15) and (L/D=0.4), and found that the boundary layer formation on diffuser surface with increasing the diffuser length enhance the mass flow rate.

It is recommended studying the effect of various curvature radius of inlet shroud and effect of various heights and angles of diffuser flange to find the optimum dimension of inlet shroud and diffuser flange collection to give optimum enhancement in coefficient of power and to minimize the induced coefficient of thrust.

REFERENCES

Cogeneration and District Heating Networks
Measures to Remove Institutional and Financial Barriers that Restrict their Joint Use in the EU-28

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Abstract—The aim of this research is to identify actions that dissipate the institutional and financial barriers that are faced by those energy projects which comprise the joint use of district heating networks and cogeneration in the EU-28. From this evaluation, institutional and financial barriers were identified, which included: distinctive competence, fuel price volatility, and much of the current regulatory framework. In order to achieve an effective removal of these barriers, and apart from generic and common actions to all the schemes, such as creating anchor loads, adopting an active marketing strategy by the local authorities, or the proposition of updating some communitarian directives on energy issues; it is also necessary to adopt those actions that respond to the casuistry of each Member State. Such actions will ultimately represent the most effective way to get a generalised implementation of energy projects that include a joint use of district heating networks and cogeneration.

Keywords: District heating networks; cogeneration; institutional and financial Barriers; distinctive competence; fuel price volatility

I. INTRODUCTION

The development of the different energy infrastructures in the local energy systems, which are often disorderly, is causing growth in the number and complexity of the resulting interactions [1]. However, the concept is different if one considers a joint use of district heating networks and cogeneration plants. In this case, as the system expands, some externalities occur in the district heating networks [2], such that the economies of scale in the provision of heat, and a more efficient use of the fuel in individual boilers (which normally operate at partial load), can be achieved [3].

The European Commission’s analysis of the evolution of the amount of cogeneration installed in the Member States between 2004 and 2008, showed an average annual growth of 0.5%, but masked a great deal of divergence in the degree of implementation of this technology.
not change the legal situation prior to that Directive. District heating networks have particular technological and institutional characteristics (such as being a natural monopoly), which makes them a non-conventional consumer good [16]. Since a market equilibrium (where the prices are equal to marginal production costs) [17] is not achieved but a monopolistic situation, production costs will fall as production increases [18]. Consequently, it is more cost effective to have a unique infrastructure dominating the market [19]. Due to the fact that under a market failure situation private investment will not exist (or at least it will be much diminished), public investment or the development of adequate regulation is necessary [20].

It is expected that in the medium term, heating loads will stabilise or decrease moderately [21]. It should be noted that improved insulation [22], optimised ventilation (with heat recovery) [23], the growth of cities (which involves the creation of heat islands), and global warming [24] will lead to a decrease in the thermal load. On the other hand, the rise in population [25] and housing comfort levels [26], will contribute to the increase of the load to be heated.

![Figure 1. Cities with a population of over 5000 inhabitants and district heating systems in the EU (Population)](image)

The current spread of district heating networks in the EU can be observed in Fig. 1. With the exception of the Nordic countries and some exceptional cases, most of these systems cover a very limited part of the city they cover.

It should be remarked that for district heating networks to achieve a penetration of over 90% in a big city [28], it may take several decades (in particular, Copenhagen spent more than 40 years), its success depending greatly on the commitment of the authorities [29].

Once a first approach to the current situation of EU-28 district heating networks and cogeneration power plants has been explicated, methods to allow the work to be reproduced will be shown in section two. In section three, the institutional and financial barriers that hamper the joint use of district heating networks and cogeneration power plants, as well as actions aimed to remove the aforementioned barriers, will be presented. In section four, a discussion about the significance of the results of the work is presented. Finally, the fifth section, reserved for conclusions, presents the implications for energy policy resulting from the actions taken to face the identified barriers.

II. METHODS

One of the most extended definitions on energy efficiency barriers was developed by Sorrell, who considered them as “postulated mechanisms that inhibit investment in technologies that are both energy-efficient and (apparently) economically efficient” [30].

Meanwhile, market failures are those barriers that are faced by consumers (and producers) in unfettered markets and that lead to a lower market penetration than optimal from an economic point of view. From a historical evaluation of the literature, this purely economic approach to explain energy efficiency barriers and its consequences on the efficiency gap was the first observed.

Despite the abundant literature, so far there is no agreement on the relative importance of each barrier. As to the nature of these concerns, its classification does not reveal substantially anything new. Among the most prevalent barrier models should be the one conducted by Weber (who classifies barriers as institutional, economical, organizational, and behavioural) [31].

However, the taxonomy adopted in this article is an adaptation of the one proposed by Chai [32], grouping barriers into the following categories: behavioural, market failures, physical constraints, and institutional and financial barriers, the latter two being the only barriers addressed in this article.

In order to identify the barriers to the implementation of district heating networks and cogeneration in the EU-28 and due to their nature, an extensive review of (updated) academic and grey literature on energy barriers was first conducted, using the preliminary results to proceed with contacting experts in this field. From their experiences, information was obtained on what the barriers are, how they can be eliminated/mitigated and if current measures proposed by the governments of their respective countries are adequate. About 150 publications were reviewed for this paper, and despite being a substantial and representative sample of the barriers identified in the literature, this number is not absolute.

It should be noted that in this paper, barriers and market failures have been differentiated and that the evaluation of those institutional and financial barriers (and not market failures) that hamper the joint use of district heating networks and cogeneration in the EU-28 (as well as the proposal of corrective measures) is the only scope of this article. The reason for this approach is the fact that market failures are well known and understood, while institutional and financial barriers (in sensu stricto), despite having a “particular relevance to the implementation of energy efficient
entrepreneurship is contrary to the competitive logic of entrepreneurs, has been problematic. This is due to the fact that as distribution network operators, they do not have the incentive to do so, and this incentive should undoubtedly come from the regulator. In this sense, the view proposed in this paper (the technological one) is in line with the approach favoured by the EU. Certainly, public intervention in energy efficiency is both an empirical and ideological issue.

The barriers identified by Chai [32], Sorrell [30], and Brown [9] were transferred to 19 experts on cogeneration and district heating networks from nine different countries (eight of whom European), who contributed either through interviews, e-mail correspondence, and/or surveys (where the experts identified the barriers and the relative importance of each of them) to give validity and reliability to the identified barriers in the literature. It should be noted that, unlike uncertainty or lack of information, these barriers are barriers in the strict sense, some of the proposed barriers by the experts consulted (such as asymmetric information and imperfect information), are themselves market failures and, consequently, will not be expanded in this paper.

III. RESULTS

A. Institutional and financial barriers

1) Distinctive competence and business model effect

If the EU-28 Member States do not create a regulatory framework aimed at converting energy efficiency into part of the utilities’ distinctive competence, then in spite of the implementation of cogeneration power plants and district heating networks being technically and economically feasible, the schemes cannot progress due to the fact that investment in cogeneration is normally less attractive than other projects that frame, focus and do not conflict with its distinctive competence. These projects also offer a lower risk rate of return, a lower intrinsic risk, and can be implemented more easily due to the fact that they do not have to overcome the barriers associated with cogeneration projects.

It is clear (and experience in other sectors with natural monopolistic characteristics has shown) that utilities will not embark on entrepreneurial or innovative activities without an incentive to do so, and this incentive should undoubtedly come from the regulator.

Empirically, it has been found that efforts to encourage focal organisations (those that serve as a reference point), such as distribution network operators, to act as institutional entrepreneurs, has been problematic. This is due to the fact that the entrepreneurship is contrary to the competitive logic that has been established in virtually all of the most developed EU countries. Innovation and change are by no means among the priorities of focal organisations that benefit from a privileged status quo.

2) Fuel and electricity price volatility

The relationship between the prices of gas and electricity is known as spark spread. The use of cogeneration will be more attractive the lower the price of gas is relative to electricity, i.e., when the spark spread is higher, and this factor is the one with the highest impact on both the internal rate of return and on the level of risk associated with a cogeneration project. In recent years, the rise and volatility of gas prices relative to electricity (low spark spread) has been a major deterrent to the expansion of cogeneration, and it is expected this trend will continue in the near future. Despite having the option to enter into long-term contracts in order to deal with the risk associated with the high volatility of gas prices in the market, the fact is that it is precisely this volatility which makes access to this contract by large users to be priced considerably higher. Consequently, the spark spread between the prices of gas and electricity shrinks, lowering the financial attractiveness of cogeneration due to the fact that the volatility experienced by the price of gas is normally not exactly reproduced in the price of electricity. This additional risk will increase the required rate of return for embarking on a project that involves the implementation of a cogeneration system with a district heating network.

In this section, it should be noted that, unlike other EU-28 members, and in order to reduce the uncertainty about the price of a particular energy resource, producers in countries with a long tradition in cogeneration, such as Sweden, can normally choose discretionally between at least two fuels, enabling flexibility to a sector of economically feasible cogeneration in Sweden.

3) Other reasons

There is no legislation at a supranational level that specifically ensures an expansion of district heating networks. Apart from the effect of the distinctive competence, the business model, and fuel and electricity price volatility, the following barriers have been identified that also hinder the development of the district heating networks:

- Long-term investment: District heating involves a long-term commitment, comparable to other public works projects of relevance. This makes it unattractive to those energy markets that have already been privatised and opened to competition, since they prefer projects with shorter payback periods. This fact, coupled with the higher risk involved in the implementation of district heating in comparison to other more conventional technologies, makes the required cost of capital greater.

- Regulatory framework: The influence of a different regulatory framework for each Member State and, in many cases, a heterogeneous approach, makes the EU-28 district heating situation completely unharmonised, and hinders the entry of those market players who have previously participated in projects of the same nature in other Member States.
- Regulation and energy price distortion: Most Eastern European countries enforce a heat price regulation to protect the most disadvantaged part of the population (mainly because welfare programs have not been introduced at a national or local level). This causes not only an energy market with distorted prices but, indirectly, prevents a proper maintenance and expansion of district heating networks, as many private investors are prevented from entering the district heating sector.

- Energy market liberalisation: Different models adopted to liberalise the energy market in the different Member States have caused a number of difficulties for market players. In particular, to the lack of integration of the energy market, joins the fact that, paradoxically, market liberalisation has caused an atomisation of the energy industry into a small group of large companies that are not interested in the development of cogeneration.

- Priorities, experience and electioneering of local authorities: Unlike health and education, local authorities in the EU-28, in addition to not having experience in the matter in question, do not consider energy as a priority, and many of the actions carried out in this area, if done, are at least "non-transparent". On the other hand, because local authorities are knowledgeable that, although beneficial to society as a whole, electorally it would be dangerous to go into debt for energy projects that are not essentially a claim or object of open discussion within the general public, they will in most cases choose not to embark on such projects.

B. Measures aimed at eliminating existing institutional and financial barriers

Throughout this section, a number of identified institutional and financial barriers related to the introduction of district heating networks and cogeneration in the EU-28 have been presented; Table 1 shows proposed reasons and measures to combat them. Each of the mechanisms proposed below shall be understood as designed to be flexible enough to meet changing requirements and to prevent redundant grants/financial support.

IV. DISCUSSION

The Community guidelines on State aid for environmental protection (Communication 2008/C 82/01) recognize that, in certain circumstances and with the objective to promote broader environmental policy goals, State aid may be necessary. These guidelines, which have been adopted in close collaboration with Member States, intend to serve as a tool for the promotion of measures to protect the environment while preventing unjustified State aid, and are fully consistent with the European Directive 2004/8/EC on the promotion of cogeneration. Therefore, the Commission's position is that State aid is acceptable under certain conditions if it serves to promote the use of renewable energy sources as well as the combined heat and power production.

However, as discussed in previous sections, the evolution of the implementation of one of the technologies that reduces emissions at a lower cost (such as district heating networks), has been in the last 25 years truly daunting for the vast majority of Member States. If the Member States really have an energy and environmental commitment, they should seek alternatives to the actions already taken. These measures should have an ultimate goal to address the barriers identified in the previous section. Even those that may be generally assumed by all Member States should be sought individually, depending on the existing level of maturity and the implementation of district heating networks.

Currently, district heating networks contribute about 10 percent of the total EU heat supply. A spontaneous change of this circumstance without the required political, socio-cultural, and market environments is unlikely. Nevertheless, if some requirements were met, it is feasible that district heating will become a major player in the European energy sector. In order for this to happen, the risks and costs associated with this type of project must be mitigated.

V. CONCLUSIONS AND POLICY IMPLICATIONS

The existing institutional and financial barriers to the implementation of district heating networks with cogeneration power plants in the EU-28 were identified. It was found that unless a substantial change in the market, or in the regulation concerning the use of the above technology, occurs, a definitive take off thereof would be difficult. The most recent EU Directives (among which Directive 2012/27/EU on energy efficiency stands out), despite being willful, are insufficient to achieve a spread of this technology according to its potential.

The reduction of energy poverty has been determined as imperative in order to achieve the targets for energy efficiency proposed within the EU-28 by 2020. Furthermore, the development of energy policies that create a symbiotic relationship between the public and the private; a more accurate assessment of environmental externalities; and the removal, in line with our proposals, of the current institutional and financial barriers for the joint use of district heating and cogeneration; are also required to achieve the EU-28 2020 targets.

For his part, it has been determined that, because currently the joint use of cogeneration and district heating networks is in most of the Member States at an early stage, the most effective way to develop sector institutions, technical regulations, and legal and contractual provisions, is that of conducting an individualised search for measures That, mainly according to their degree of maturity and existing implementation in each Member State, evolve and lead as the system expands to an appropriate regulatory regime. Based on what is stated here, that would eliminate the institutional and financial barriers that those energy projects involving the joint use of cogeneration and district heating networks face.
### Reasons and Measures Proposed to Address the Institutional and Financial Barriers that Hamper the Development of District Heating Networks and Cogeneration in the EU-28

<table>
<thead>
<tr>
<th>Reasons</th>
<th>Identified barrier</th>
<th>Measures proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of a policy framework that aims to make energy efficiency part of the distinctive competence of the utilities. Generally, focal energy organisations benefiting from a privileged status quo lack a desire for innovation and change. Intrinsic risk of these infrastructures and the payback period.</td>
<td>Distinctive competence and business model</td>
<td>The national energy regulators of each Member State were proposed to bear the responsibility of encouraging the participation of these organisations. In order to mitigate the reluctance of the focal energy organisations the risk should be completely eliminated, imposing a discount rate of 3.5%. Forcing the national energy regulator of each Member State to involve focal organisations on energy infrastructures of this kind. The objective would be for the action to not only be developed and implemented in a particular Member State but also to become part of the distinctive competence of local energy organisations.</td>
</tr>
<tr>
<td>High gas price volatility. Low spark-spread in recent years. Payback period longer than other energy projects. Risk of implementation higher than other, more conventional technologies.</td>
<td>Fuel and electricity price volatility. Long-term investment</td>
<td>Provision of aid for electricity produced from high-efficiency cogeneration power plants, not only would reduce significantly the payback of the investment and would provide a guaranteed income over the life-cycle of the plan and the district heating networks but also would mitigate the perceived risks. Modification of payment terms of district heating networks providers. High degree of public sector involvement. Local authorities have had the ultimate responsibility for the final push of the development of district heating networks and also to carry out standardised contract terms in order to attract users. Obligation to the newly built power plants to have a minimum efficiency of at least 70%. This would make cogeneration a low-cost alternative.</td>
</tr>
<tr>
<td>Lack of harmonisation of the rules relating to district heating for the EU-28 Member States.</td>
<td>Regulatory framework</td>
<td>Creating anchor-loads representing a load of about 80% of the total capacity of the district heating network. Updating the Directive 2009/72/EC in order to explicitly allow to provide long-term contracts to those suppliers of technologies that contribute to compliance with environmental obligations of the EU-28 Member States and also with customer rights. Creating an organisation belonging to the central government that would develop the political framework and would act as a leader in the development of district heat networks.</td>
</tr>
<tr>
<td>Lack of social assistance programs at the national or local level in some of the Eastern European countries belonging to the EU-28.</td>
<td>Regulation and distortion of energy prices</td>
<td>Introduction of assistance programs at a national or at a local level in those Member States where they are not present, in order to ensure unnecessary the implementation of heat prices that protect the most vulnerable part of the population, as they would ultimately impede the proper maintenance and expansion of district heating networks. Implementation of tariff differentiation or other form of compensation for those cases where district heating networks are more expensive for the consumer than the conventional alternative.</td>
</tr>
<tr>
<td>Lack of integration of the energy market. Atomisation of the energy industry.</td>
<td>Energy market liberalisation</td>
<td>Implementation of a pure carbon model in which the shadow price of carbon would be fully assigned to the combustion of fossil fuels, would fully remunerate the emissions released into the atmosphere due to more efficient schemes through the carbon price.</td>
</tr>
<tr>
<td>Generally, local authorities do not consider energy to be a priority. Potential electoral danger for the debts that would result from the execution of this type of energy projects.</td>
<td>Priorities, experience and electronising of the local authorities</td>
<td>Make adjustments to planning and building regulations, showing builders the potential benefits of its use. Implement a strategy of institutional and active marketing by local authorities with programs of promotion and dissemination of the technology. Conduct feasibility studies technologies/innovative applications, demonstration projects of cogeneration power plants and district heating networks. Perform an institutional innovation through the creation of a public company only in those Member States that do not have favourable market conditions and where the above measures have proven ineffective. This measure is based on the fact that if a given government is determined to create companies that combine all the necessary skills for the implementation of district heating networks with cogeneration facilities, then transaction costs of the technology will decrease significantly</td>
</tr>
</tbody>
</table>
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Evaluation of the cost of using power plant reject heat in low-temperature district heating and cooling networks
(Authors: Antonio Colmenar Santos, David Borge Diez, Enrique Rosales Asensio, Patricia Sánchez Sánchez)

Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle
(Authors: Jan Bitter, Stephan Printz, Kristina Lahl, René Vossen, Sabina Jeschke)

Research on Electrical Brake of A Series-parallel Hybrid Electric Vehicle
(Authors: Xiaoxia Sun, Lining Yang, Chunming Shao, Xin Li, Guozhu Wang, Yusong Yue)

Numerical analysis and model-based control of energy recovery ventilator in HVAC system
(Authors: Nam Khoa Huynha, Hua Lib, Yeng Chai Sohc, Wenjian Caic)
Evaluation of the cost of using power plant reject heat in low-temperature district heating and cooling networks

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Abstract—The purpose of this paper is to assess the economic impact following as a result of the conversion of conventional stations to cogeneration plants connected to a system for distributing heat and refrigeration. The analysis will be carried out through a financial evaluation in order to assess yearly variations of the whole scheme expenditure. In particular, yearly capital and operating costs of supplying cold and heat to urban areas that represent weather conditions in northern, central, and southern Europe were studied. In the base case scenario, today conditions are represented; they will be compared with alternative scenarios in which existing conventional thermal power stations will be converted into cogeneration plants. This research work contributes to the pool of existing knowledge by giving a (so far not addressed) weather centered system perspective. From the conducted evaluation, it was found that, in the case of deciding to convert the studied conventional thermal plants into cogeneration plants, investing in the necessary infrastructure associated means that yearly expenses for the power plants located in Oldenburg-Wilhelmshaven, Bristol, and Cartagena would decrease by 215, 89, and 192 million euros respectively, making this technology a highly attractive option from economic, energetic, and environmental perspectives.

Keywords: Low-temperature district heating; cooling networks; cogeneration; conversion of thermal power plants; weather conditions

I. INTRODUCTION

As a general rule, the newly-built thermal generating stations are designed as condensing power stations or as cogeneration plants—most of them having the flexibility to switch back to condensing mode on a seasonal basis without the loss of efficiency for the latter. The technical difference between an electricity-only power plant and a cogeneration plant suitable for district heating networks lies in the fact that with the latter, there should be some way to condense the mixture of gas and saturated vapour at a superior temperature. It is accomplished in cogeneration plants with extraction-condensing turbines that use the exhaust steam from the low-pressure turbine stage in a heat exchanger. The more steam enters the condenser, the smaller the amount of electricity generated (due to the fact that a lower amount of gas and saturated vapour is leaving the low-pressure turbine).

Depending on the type of plant, power rating, and location, the extra cost for the cogeneration version varies between 10 percent and 45 percent [1]. If the aim is having a cogeneration plant as efficient as possible, the replacement of the low-pressure turbine (or even replacement of the high-pressure one) will likely be compulsory [2]; it should be noted that although this is an expensive solution, it will always be much cheaper than building a new power station.

In those countries where the technology of cogeneration and district heating networks is more advanced, many of the units of thermal power plants converted into cogeneration plants have been (or will be) replaced by more modern units located on the same site, dismantling the old units or using them as a reserve. In any case, it should be noted that other non-technical factors, such as the energy planning regime, will also come into play and that under no circumstances can all existing power plants be converted into cogeneration plants, having the actions to be taken considered individually.

It should be noted that, assuming that the total conversion (of all units) of a thermal power plant provides a higher heat than needed by the loads, it is possible to proceed to a partial conversion of the plant at an obviously inferior cost. If the destination of the heat were low-temperature district heating networks (with a lower energy demand than conventional district heating networks), the number of units to convert would obviously decrease. The conversion is achieved by a modification/replacement of both the LP turbine and the condenser. Alternatively, one unit may go into a partial modification to provide a warmer heat, extracting from the space between the high pressure turbine and the low pressure turbine heat at a high temperature and pressure. This solution would have a lower overall efficiency than the replacement of the low-pressure turbine. The best option in any case depends...
on a particularised assessment of the generating station and on the end-use purpose and heat requirements.

To understand the importance of using low-temperature district heating networks, the Carnot cycle has to be considered. According to this cycle, the greater the difference between the inlet temperature and the heat rejection temperature (the one that leaves the low-pressure turbine), the greater the efficiency of the power plant [3].

In the scientific literature, it is possible to find a large number of research papers exploring the economic and/or environmental impacts of the joint use of cogeneration and district heating networks. The research undertaken by Trygg and Amiri who analysed, from a European system perspective, the most cost-effective technology for the production of cooling [4]; or the investigation conducted by Persson and Werner, who carried out an aggregated quantitative analysis of current average EU heat recovery levels in district heating systems [5].

However, the potential repercussions that weather conditions have on the feasibility of the joint use of district heating networks and cogeneration have not been given the same attention, so a study that addresses them is necessary. From a deeper survey of grey literature and updated literature related to the topic addressed here, it was possible to find that – even though there are plenty deal of different approaches – this paper undoubtedly contributes to the pool of existing knowledge by giving a weather centered system perspective By performing this thorough literature review, we ensure the originality of the idea and method here presented.

Furthermore, the proposed method here presented improves analysis in the sense that a systematic and easy approach manages to make comparisons among different district heating networks systems regardless of their sizes and locations.

II. MATERIALS AND METHODS

Knowing the needed energy to provide heating and cooling to a specific number of consumers and from various techno-economic parameters of the selected conventional thermal power plants, the three base cases will be sustained; they will include costs and revenues of the plants as well as the expenses associated with the loads of consumers utilising equipment available as of today. This assessment will include the cost of capital, renovation costs, operational and maintenance costs, and revenues from electricity generation. Please bear in mind that, for all the paper, the heat we are interested in and refer to with the term “reject heat” is the waste heat cogenerated from the “electrical generators” of the thermal power plants and not the un-recovered heat of a previously existing cogeneration plant.

For the evaluation of the cases in which the conventional thermal power station is converted into a cogeneration plant, the cost of this conversion, infrastructure investment (district heating/cooling networks), buildings adaptation costs, and electricity prices are taken into account (in case heat accumulators that can cope with a demand for one to three days are included, it is possible to presume a power optimum instant selling).

To make the economic analysis, annual costs of the systems for the specified cases, net electricity (difference between the electricity measured at the busbars of the powerplant and its consumption), primary energy used, and carbon dioxide emissions (calculated in each case directly from the primary energy) were compared.

A. Annual costs

Annual costs of the system were calculated for each case using (1) [6].

\[ C = AC + m \times X + v \times X + f - REV \]  

\[ A(n,d) = \frac{d \cdot (1+d)^n}{(1+d)^n-1} \]

1) Annualised capital costs

The annual outgoing aggregate of all future cash flows of the facilities are assessed employing equations (2) and (3) [7]:

\[ AC = \sum_{t=1}^{T} A(n,d) \cdot c_t \cdot X \]  

\[ A(n,d) = \frac{[d \cdot (1+d)^n]/[(1+d)^n-1]} \]

Because district heating is an infrastructural investment, and in order to be consistent with the Directorate-General for Regional and Urban Policy proposal, a (social) discount rate of 3.5% was chosen because it was considered that such projects have a positive impact on the collective as a whole [8]. The result of using other higher discount rates (5.5% and 7.5%) will be checked later in a sensitivity analysis.

The reason for choosing these discount rates is that they are, on the one hand, the social discount rates proposed by the EU-28 for competitive regions (3.5%) and for cohesion regions (5.5%) [9] and on the other hand, 7.5% is one of the most widely used discount rates for the evaluation of such projects [10].

In this article, it will be assumed that facilities are renovated, which obviously will have a positive impact in their lifetime or technical life and will involve higher annual maintenance costs due to this economic life extension [11].

In addition to this, it is assumed that the inflation and the discount rate will remain constant over the useful life of the project, so the levelised cost of energy can be expressed in €/MWh, thereby eliminating the impact of inflation and enabling the use of a constant currency (constant euros) tied to the current year. Ordinarily, life-cycle costing techniques use (as in this paper) a real discount rate, which is entirely consistent with the constant currency analysis carried out in this article. It should be noted (previous studies at European level prove so) that the feasibility of the proposed actions in this article does not show a “high sensitivity” to changes in oil prices, natural gas, and coal, so the sensitivity analysis is performed only for the discount rate to be used.
2) Fixed running and preservation expenses

Generating stations are regularly renovated to extend their useful lives, so it has been considered appropriate to add to the annual fixed costs of operation and maintenance (which average around 2% of the investment cost) [12] an amount equal to them to satisfy renovation costs. It should be noted that the estimation of the latter presents a significant challenge and that, depending on the type of plant, maintenance performed, age, and the country in which the plant is located, annual fixed costs of operation and maintenance may be anywhere from negligible to representing 15% or more [13] of the investment cost of the plant (due to these circumstances, it was considered that 2% is a quantity general enough to represent the renovation costs that have to be faced by the typical power plants of Western Europe).

3) Variable running and preservation expenses

Apart from the fixed operating costs, it has been considered a variable running and preservation expense in a balanced relation to produced electricity [14].

4) Combustible expenses

Mainly using data obtained from Europe's Energy Portal, different fuel prices for the residential sector and the industrial sector (assuming here that the power plant will acquire the combustible as an industrial user) will be adopted.

5) Revenues resulting from the sale of power

It has been accepted that sales of electricity take place in a cash market, taking into account data obtained from the electricity operators – EEX (for Oldenburg-Wilhelmshaven), Elexon (for Bristol), and OMEL (for Cartagena).

It should be noted that, in the analysis carried out in this paper, a cost boundary around the system (power station, heat consumer, power consumer) is drawn and then added up the costs of fuel and capital under the combined heat and power district heating schemes versus the current scheme.

B. Conversion and emission factors

Aside from the coal and natural gas used by thermal power plants and domestic consumers, the primary energy demand includes the electricity sent to the grid [15].

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Type</th>
<th>Fuel used</th>
<th>Electrical efficiency in condensing mode, %</th>
<th>Energy used to generate electricity, TWh</th>
<th>Output power, TWh</th>
<th>Losses in transmission and distribution networks, TWh</th>
<th>Conversion factor</th>
<th>Emission factor, tCO₂/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilhelmshaven</td>
<td>Coal power plant</td>
<td>Coal</td>
<td>46</td>
<td>9.51</td>
<td>4.37</td>
<td>0.39</td>
<td>2.39</td>
<td>0.50</td>
</tr>
<tr>
<td>(E.ON)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seabank</td>
<td>Combined cycle power plant</td>
<td>Natural gas</td>
<td>55</td>
<td>12.18</td>
<td>6.70</td>
<td>0.60</td>
<td>1.99</td>
<td>0.24</td>
</tr>
<tr>
<td>(Bristol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Fangal</td>
<td>Combined cycle power plant</td>
<td>Natural gas</td>
<td>55</td>
<td>12.81</td>
<td>7.04</td>
<td>0.63</td>
<td>1.99</td>
<td>0.24</td>
</tr>
<tr>
<td>(Cartagena)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

The annual energy required to generate the supply of the energy carrier electricity is calculated according to the typical efficiencies of the most extended power generating technologies available today and on the consideration of a losses in transmission and distribution networks of 9% for the electricity mix of each country. The primary energy conversion factors calculated for the plants evaluated [16], the assumed efficiencies [17] and the emission factors used (note the divergence of the same depending on the country studied and bibliography used) [18], are presented in (Table 1).

III. CALCULATION

For each of the cities of Oldenburg-Wilhelmshaven, Bristol, and Cartagena, its heating and cooling demands have been taken into account. Each of the cases considered are represented as follows:

1) Current Situation (Base Case)

In the current situation, electricity is sold in the cash market by the generating stations without providing heat to any system for distributing it. Refrigeration is provided through conventional vapour-compression refrigerators and evaporative coolers.

To assess this case, the following technologies have been considered:

- The conventional thermal power plant assigned to Oldenburg-Wilhelmshaven has been the coal power plant at Wilhelmshaven (E.ON); for Bristol, the assigned plant has been the combined cycle power plant of Seabank; meanwhile, the thermal combined cycle power plant of El Fangal has been chosen to conduct the evaluation for Cartagena.
- Individual heating and cooling equipment using gas and electricity

2) COGEN-a1 Case

In this case, the conventional thermal power plants have been considered as converted into cogeneration plants through their conversion and not through the construction of completely
new plants; the investment associated with the infrastructure necessary to enable the implementation of low-temperature district heating networks has also been taken into account. Unlike COGEN-b and COGEN-c, cooling is carried out through electrical refrigeration equipment. Introducing a thermal energy storage, it is plausible to suppose that the cogeneration plant will provide the same number of hours of electricity that the conventional generating station of the current situation has.

It should be noted it is a cautious supposition, as cogeneration plants typically have an electrical production duration higher than conventional power plants, which adds an additional benefit to the system.

Please note that this additional heat modifies the economic conditions of operation of the plant due to the reduction of operational costs and increased profitability [19].

The option COGEN-a1 has been compared to the Base Case alternative performing a sensitivity analysis. In the Base Case alternative, current heating appliances are kept in buildings, not producing any improvement in those nor therefore investment. For the calculation of the case COGEN-a1, the following technologies and considerations have been taken into account [20]:

- Costs of retrofitting existing conventional power plants into cogeneration plants; transmission pipelines from power plants to district heating networks; district heating networks of cities; and accumulators in district heating networks.
- Centralised natural gas boiler systems for peak demand; connection costs of individual housing and heat exchangers; and individual cooling appliances.

3) COGEN-a2 Case
The COGEN-a2 case is similar to COGEN-a1, but building a new cogeneration plant instead of converting the conventional thermal power station.

4) COGEN-b Case
Unlike the case COGEN-a1, COGEN-b assumes (individual) absorption units use the district heating network for cooling. For the calculation of the case COGEN-b, the following technologies and considerations are taken into account:

- Costs of retrofitting existing power plants into cogeneration plants; transmission pipelines from power plants to district heating networks; district heating networks of cities; and accumulators in district heating networks.
- Central heating (boilers) using natural gas for peak demand; cost of heat exchangers and connection to buildings; and absorption units used as individual cooling devices.

5) COGEN-c Case (trigeneration)
Unlike the cases COGEN-a1-a2, in COGEN-c, it is assumed that the cooling is obtained through a district heating network and integrated absorption chillers (which refrigerate the district energy scheme utilising the waste heat cogenerated from the “electrical generators”). It is assumed that absorption units are located between the transmission pipelines and the district heating networks of the cities.

In the case COGEN-c, the following technologies and considerations are assumed:

- Cost of conversion of existing conventional power plants into cogeneration plants; transmission pipelines from power stations to district heating networks; district heating networks; district cooling networks; gas central heating (boilers) for peak demand; accumulators in district heating networks; and absorption refrigeration units for district cooling.
• Cost of heat exchangers and connection to buildings; individual cooling appliances.

A. Power plants and district heating and cooling networks

Even for Oldenburg-Wilhelmshaven and in order to simplify the analysis, it has been supposed that the district heating network is implemented together as a whole (in this case, the worst option is assumed, which is that in which the district heating network is located as far as possible, in this case in Oldenburg).

Furthermore, it is assumed that all the heat accumulators of the district heating networks evaluated have a capacity of 50,000 m³ and the ability to provide services such as load following in order to integrate the maximum amount of renewable energy. Due to its higher cost and lower uptake than atmospheric tanks, it has not been contemplated the use of seasonal thermal energy storage.

B. Demand

The number of consumers to be supplied by the district heating network is estimated for each city through the peak heat output of the cogeneration plants in the coldest month (January) [21], having to take into account that they should cover about 50-70 percent of the peak demand (Fig. 1). It was assumed that the loads related to residential buildings correspond to single-family homes (which is a fairly conservative assumption) [22] and that those that refer to other loads are offices.

For the cost/benefit analysis, it has been considered that the losses from the cogeneration plant and loads are 9% over the year, and that heat distribution losses during peak demand in winter are 6% [23].

IV. RESULTS

In this section, the results of the case studies of selected cities will be presented. Taking into account that district heating networks were considered for all cities, the COGEN-a1 option represents a conventional thermal power station converted into a cogeneration plant through modifications or changes of the turbines; meanwhile, COGEN-a2 will represent a variant of COGEN-a1 in which a generating station will be built from the beginning. Due to the fact that, in comparative terms and relative to Cartagena, the cooling demand is not significant for Oldenburg-Wilhelmshaven and Bristol, only other alternatives to the current cooling for Cartagena have been considered (COGEN-b and COGEN-c cases).

A. Oldenburg- Wilhelmshaven

The results indicate that, following the introduction of district heating networks, a reduction in the annualised cost of about €215 million would be achieved. This quantity results from subtracting the Base Case total system cost (roughly €510 million) at a discount rate of 3.5% per year from the COGEN-a1 Case total system cost (roughly €295 million). If these results were compared with those obtained for Bristol, it will be appreciated that because of a worse performance in terms of electricity production, the thermal generating station of Wilhelmshaven will have a greater annualised savings than in the case of Bristol. Meanwhile, and with regard to the overall efficiency, it will be similar both for cogeneration plants using coal as in cogeneration combined-cycle plants, so that the total efficiency gains will be greater in Oldenburg-Wilhelmshaven than in Bristol.

In the case of converting the conventional coal thermal power plant of Wilhelmshaven into a cogeneration plant and implementing a district energy system, a 2.1 terawatt-hour source energy abatement is reached. Consequently, carbon footprint will be lowered in 1.05 megatonnes, and net electricity would be reduced in 0.54 terawatt-hours.

1) Sensitivity analysis

To study its impact on profitability, a sensitivity analysis was carried out for three different discount rates (3.5 percent, 5.5 percent, and 7.5 percent). Although the results show that the discount rate has a significant impact in absolute terms (the total system costs when “Cogen-a1” and “Cogen-a2” are evaluated at a discount rate of 7.5% are, respectively, 33% and 25% higher in comparison when a discount rate of 3.5% is used; see Table 10), the conversion or construction of a new cogeneration plant with the necessary infrastructure remains profitable, even with high discount rates.

B. Bristol

It is assumed that the conventional thermal power plant of Bristol, with a nominal power of 1140 MW, before the conversion, produces 6.7 TWh of electricity per year. Once the plant is converted into a cogeneration plant, revenues resulting from the sale of electricity will decrease due to the fact that, for the same amount of fuel used, electricity generated will decrease, for this particular case, around 10%.

For loads located in Bristol, the annual costs of providing heating, hot water, and cooling from the existing conventional thermal power plant (its electricity produced is also shown) for three different cases – Base Case, COGEN-a1, and COGEN-a2. Note that when the Base Case (roughly €291 million for a discount rate of 3.5%) is compared with COGEN-a1 (roughly €202 million), the annual costs of heating are reduced by €89 million due to the implementation of the district energy system. If a cogeneration station were to be constructed from the beginning (COGEN-a2 at a discount rate of 3.5% would be roughly €237 million), savings of €54 million would be achieved.

Following the introduction of low-temperature district heating networks, primary energy savings of 1.63 TWh and a reduction in CO₂ emissions of 0.39 million tonnes will take place.

1) Sensitivity analysis

In order to evaluate its influence on the result, a study of how the feasibility of the system can be apportioned to different sources of uncertainty in its input was conducted. There is a significant impact in absolute terms. For all the cases, converting a conventional thermal power plant into a cogeneration plant was advantageous; in turn, building a cogeneration plant from the beginning only was worthwhile when low interest rates in discounted cash – the ones proposed by the EU-28 for competitive regions (3.5 percent) and cohesion regions (5.5 percent) – were employed.
C. Cartagena

The annual costs of providing heating, hot water, and cooling (besides electricity) from one of the existing thermal power plants in Cartagena (powerplant of El Fangal) are presented for loads located in this city.

In the Base Case, costs of providing heating and cooling to Cartagena for the current situation (having taken into account for this the cost of the different actual elements and the revenue from the electricity sold), have been calculated.

In the case COGEN-a1, annual costs of providing heating and cooling to the city of Cartagena, assuming the use of low-temperature district heating networks, were calculated. After evaluation, it was concluded that, in case of using this technology, annual losses would be £3 million. If a new cogeneration plant were built (COGEN-a2), the annualised cost will increase £31 million.

COGEN-b assessed yearly heating and cooling expenses, assuming the use of district heating networks and absorption cooling units. The annualised savings of heating and cooling is £191.5 million.

The COGEN-c case estimated the annual costs of heating and cooling in Cartagena, assuming that district energy networks (including refrigeration networks) as well as central refrigeration technologies are used. The annualised expenses reduction was £135 million.

All annual costs and savings related to Cogen-a1, Cogen-a2, COGEN-b, and Cogen-c are obtained by subtracting the total system costs for the Base Case at a discount rate of 3.5% from the total system costs for each of these systems.

In the case of converting the thermal power plant of El Fangal into a cogeneration plant and of using the system proposed for this case (COGEN-c), a 1.3 terawatt-hour saving is reached. Consequently, the carbon footprint would be lowered by 0.32 megatonnes and the net electricity would decrease by about 0.82 terawatt-hours.

1) Sensitivity analysis

In absolute terms, results are greatly influenced by discount rate changes. It can be seen that for all discount rates used, options (COGEN-b-c) are more profitable than the Base Case; conversely, no matter what discount rate is used, it is not profitable to convert the existing thermal power plant or to build a new cogeneration plant using the options (COGEN-a1-a2).

V. DISCUSSION

Assessing the cost of three district heating schemes that respectively represent typical weather conditions in northern, central, and southern Europe (Oldenburg-Wilhelmshaven, Bristol and Cartagena), it has been possible to appreciate the potential reduction in expenditure as a result of both converting existing conventional thermal generating stations into cogeneration plants as well as investing in a low-temperature heating and cooling infrastructure (the latter only feasible for the weather conditions in southern Europe).

The implemented method (which considers as main elements the power plant and the needed energy to provide hot water, heating, and cooling to a specific number of loads) that sustains the economic analysis conducted for three cities of the EU-28 with different weather conditions constitutes a valuable element in itself because not using specific software and using simple and immediate calculations allows the evaluation of the potential benefits of retrofitting existing power plants into cogeneration plants with an associated heating network infrastructure (and, in the case of Cartagena, also with a cooling one), being, therefore, particularly suitable for studies with analogous purposes.

From the quantitative evidence presented in this paper, it has been shown that the implementation of district energy systems in Oldenburg-Wilhelmshaven, Bristol, and Cartagena would reduce CO₂ emissions by 41 percent, 30 percent, and 23 percent, respectively, with the obtained net primary energy savings being similar. The savings resulting from the conversion of a conventional thermal power plant into a cogeneration one are higher in Oldenburg-Wilhelmshaven, the location with the coldest weather (and, therefore, the longer period of heating). The greatest savings are also due to the fact that, unlike the combined cycles of Bristol and Cartagena, the plant of Wilhelmshaven is a thermal coal power plant, so its electrical efficiency is lower, and its overall efficiency improvement when converted into a cogeneration plant is increased in a greater proportion.

From the evaluation of the results, some conclusions and implications for energy policy of paramount importance can be drawn. On the one hand, and for the case of Oldenburg-Wilhelmshaven, it has been shown that even with having to transport heat over long distances (more than 60 km) through heat transmission pipelines, from the joint implantation of cogeneration plants and district heating networks, significant savings and benefits from an economic and environmental perspective can be achieved. It should be noted that because district heating networks are of the low-temperature type and heat to be transmitted considerable, resulting distribution losses were lower, which has been determinant in the feasibility of all district heating schemes.

Equally striking is the case of the power plant located in Bristol. The UK, due to its population density and climatic conditions, has great potential for the implementation of district heating networks; however, and if the countries of southern Europe are excepted, diffusion is the lowest of all the EU-28. From the evaluation of the case for the power plant of Seabank, it could be seen that, like in the case of the power plant of Wilhelmshaven, great economic and environmental benefits would result from the implementation of cogeneration plants and low-temperature district heating networks.

For its part, and for the case of the power plant of El Fangal (Cartagena), it was found that although the use of district heating is not suitable for the weather conditions in Cartagena, not least is the fact that, if district heating networks and absorption refrigeration units or district heating and cooling networks were used in conjunction, economic and environmental benefits would be at the same level of
VI. CONCLUSIONS

From the conducted evaluation, it was found that, in the case of deciding to convert the studied conventional thermal plants into cogeneration plants, investing in the necessary infrastructure associated means that yearly expenses for the power plants located in Oldenburg-Wilhelmshaven, Bristol, and Cartagena would decrease by 215, 89, and 192 million euros respectively, making this technology a highly attractive option from economic, energetic, and environmental perspectives. This claim is supported by the fact that, were power plants to be converted into cogeneration plants, net electricity consumption would be reduced by about 545 GWh, 520 GWh, and 815 GWh respectively for the cases of Oldenburg-Wilhelmshaven, Bristol, and Cartagena (which represents savings of 13.5%, 8.5%, and 12% in comparison to the current situation). Furthermore, and in relation to the environmental benefits, CO₂ emissions would be reduced by about 1050 kt, 390 kt, and 320 kt respectively for the cases of Oldenburg-Wilhelmshaven, Bristol, and Cartagena (which represents savings of 40%, 29%, and 23% in comparison to the current situation).

Consequently, this proves the attractiveness of the plan in economic, energetic, and environmental ways. From the evaluation conducted, it was proved that even though important, weather conditions are not determinants of the feasibility of an infrastructural project entailing the joint use of district heating networks and cogeneration, and that, taking into account the characteristics of each location, alternative solutions (such as using absorption units that utilise districts heating networks for cooling or using heating networks and integrated absorption chillers), are advantageous from an economic, environmental, and energetic perspective. This conclusion is of paramount importance as the projects evaluated in this paper are similarly-sized district heating schemes, and consequently, the outcome of the analysis conducted in this research is certainly valuable for comparative, technological, and political purposes as it proves that weather conditions are not an impediment to the spread of such a marginally used scheme in southern Europe as district heating networks and cogeneration are. As a matter of fact, this analysis is instrumental in proving wrong the idea that the use of district heating networks and cogeneration is not an economically advantageous scheme in southern European weather conditions. Finally, it was concluded that, in the event of using different discount rates of 3.5% (the one proposed by the Directorate General of Urban and Regional Policy of the EU), the feasibility of projects involving the joint use of cogeneration plants and district heating networks would be greatly diminished. This being the maintenance of the aforementioned discount rate of capital importance if the EU’s 28 member states aim to have safe, clean, and efficient energy enacted by one of the three priorities (in particular, by the Societal Challenges) of the Horizon 2020 of the EU-28.

ACKNOWLEDGMENT

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Abstract—The energy revolution’s goal is to transform the current energy system into a sustainable system based on renewable energy technologies (RET). Even though RET are generally acknowledged as low-emission technologies with positive connotations, there are also negative impacts on ecological, economic and social environments throughout their life cycle. In order to support decision makers in building a sustainable energy system, comprehensive and easily understandable sustainability assessment-tools are required. Current approaches based on methods like Life Cycle Assessment or Multi-Criteria-Decision-Analysis have weaknesses in terms of comprehensiveness, processing of uncertainty and subjectivity, and visualization of results. In this paper, the holistic Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle (Fuzzy-IST) is proposed in order to resolve these weaknesses. Quantitative and qualitative Basic Sustainability Indicators of all sustainability dimensions and lifecycle stages are hierarchically processed in a multi-stage fuzzy system. This results in seven crisp Sustainability Dimension Indices and a General Sustainability Index. The crisp values are then visualized in a color-coded Integrative Sustainability Triangle to provide an easy and intuitive interpretation of the results. This allows for the identification of deficits in all dimensions and the deduction of fields of action to improve the overall sustainability of RET.

Keywords—Fuzzy Logic; Fuzzy-IST; Integrative Sustainability Triangle; Renewable Energy Technologies; Sustainability Assessment

I. INTRODUCTION

In the light of climate change, scarce resources, such as fossil fuels, and increasing environmental awareness, the energy revolution – i.e. the change to a sustainable energy system – is a widely recognized political, social and technological goal. The supporting pillar of the energy revolution is the expansion of renewable energy technologies (RET) [1]. Positive impacts on ecological, economic and social environments throughout the life cycle of RET, such as low emissions, low resource consumption and job growth, stand opposed to their negative impacts, such as noise pollution, fluctuating energy production and effects on biodiversity [2–4].

In order to investigate the influence of these impacts on the overall sustainability of RET, there are several approaches for sustainability assessments. These include, but are not limited to, Life Cycle Sustainability Assessments (LCSA) and Multi-Criteria-Decision-Analyses (MCDA). All approaches have their own benefits and deficits [2,5]. The approaches differ in focus, effort for data acquisition and implementation, and result presentation [6,7].

The objective of this paper is to propose a novel, integrated approach for sustainability assessment of RET, which includes qualitative and quantitative indicators that depict all dimensions of sustainability and all life cycle stages. An overview of the state of the art of techniques used in sustainability assessment for RET is given. The proposed method is described and conclusions are drawn.

II. STATE-OF-THE-ART

Sustainability is a complex, multi-dimensional construct. To process the complexity adequate models, measures and tools for capturing and assessing sustainability are necessary. The objective of a sustainability assessment is to provide decision makers with the necessary information and context required to support them in defining short- and long-term actions necessary for sustainable development [6,8,9]. The following sections give an overview of the systematization concepts of sustainability, indicators and indices, as well as methods for sustainability assessment.

A. Systematization Concepts for Sustainability

In order to successfully carry out a sustainability assessment, it is essential to answer one question first: What is sustainability [10]? As of yet there is no undisputed definition, merely a commonly accepted notion of sustainability. First introduced in the 18th century, this notion was developed from an approach to careful arboriculture, into a holistic concept that tries to reconcile human economic activities with the carrying capacity and exhaustibility of the natural environment and human needs – today and in the future [11]. Based on this notion there are three dimensions to sustainability: ecology, economy and social issues. They have interdependencies and intersections [12]. Due to its multi-dimensional properties, there are several approaches to systemizing sustainability.

The three sustainability dimensions are either considered separately or integrated. For instance, the triple-bottom-line (TBL) approach systemizes ecology, economy and social...
issues as three pillars standing side-by-side, carrying sustainability as a roof – implying a separation of the different dimensions [13]. Another TBL-based modelling approach uses intersecting circles to represent the dimensions so as to emphasize their overlaps [13]. Systemizing the sustainability dimensions in a triangle allows for the continuous classification of elements, like for example indicators or fields of action, between two dimensions. All of these systematization concepts are based on separate, partially intersecting sustainability dimensions [13].

Integrative systematization approaches represent the complexity of sustainability, i.e. – the interdependencies and connections of all three dimensions [13]. The Integrative Sustainability Triangle (IST) further extends the classical sustainability triangle by adding discrete fields inside the triangle, thus allowing for a classification of elements, such as indicators or fields of action, in all three dimensions (see Figure 1). This approach is based on Gibb’s Triangle, which is used to visualize three-component mixtures in chemistry or material sciences [12].

The IST does not only systemize the three core dimensions; it also provides a structured visualization of sustainability. Furthermore, it facilitates the allocation of elements to the different fields. By connecting the elements with arrows, interdependencies can be depicted. By using a color code, levels of attainment within fields can be visualized [12].

### B. Indicators and Indices

Methods for sustainability assessment are classically based on sustainability indicators. Indicators include “results from the processing (to various extents) and interpretation of primary data” [10]. Sustainability is a complex and, at times, subjective field based on different perspectives. In order to process these characteristics, quantitative and qualitative indicators must be considered in sustainability assessments [6]. Both types of indicators either have a specific unit or are dimensionless. Depending on their application and the availability of data, they are generally based on theories, empirical analyses, pragmatism or intuition [10].

Sustainability indicators are either assessed separately or combined with one another. Indices are combined indicators that are based on the transformation and aggregation of sub-indicators with different units, to a single, dimensionless number [10]. The author of [4] proposes a hierarchical aggregation of Basic Sustainability Indicators (BSI) to a General Sustainability Index (GSI), shown in Figure 2. The aggregation is facilitated by scaling, normalization and weighting methods. Thus indicators of different units are made comparable and the complexity of the sustainability assessment is reduced by combining indicators [4,14].

### C. Methods for Sustainability Assessment

Existing models, measures and tools for sustainability assessment analyze sustainability and sustainable development from diverse angles and with wide-ranging focuses. They are based on different scales, elements and aspects that consider various levels, including product, process, company and political levels, which in turn can be further divided into regional, national or international levels [9,14].

#### 1) Life Cycle Approaches

One prominent method for sustainability assessment is Life Cycle Analysis (LCA). This approach is based on analyses of material and energy flows and their impacts over the entire life cycle of the object under investigation. It historically focuses on ecological indicators, such as material consumption, emissions and land use. In recent years, though, new life cycle approaches have emerged that focus on the other two sustainability dimensions. Thus, on one hand, Life Cycle Costing (LCC) focuses on economic aspects by considering all monetary costs throughout the life cycle in the set system. On the other, Social Life Cycle Assessment (S-LCA) focuses on social aspects by incorporating the social impacts of material and energy flows in the analysis. LCA, LCC and S-LCA are all based on ISO 14040 (2006) and ISO 14044 (2006) [5].

The author of [15] proposes a framework for the combination of LCA, LCC and S-LCA in order to reach a LCSA. He underlines the importance of an integrated assessment by interpreting the results of each life cycle approach next to the others, rather than simply summing them up. As of yet there is no universal standard for LCSA [5]. Whilst S-LCA is equipped to process qualitative and quantitative data, LCA and LCC are solely based on quantitative indicators, which facilitates the mathematical calculations necessary for the assessment, but the it might be considered incomplete due to relevant qualitative indicators.
being omitted [5,10]. For all life cycle approaches the costs of data acquisition, consolidation and processing are high [16].

2) Multi-Criteria-Decision-Analysis Approaches

MCDA approaches are commonly used in sustainability assessments in order to process quantitative and qualitative inputs for all sustainability dimensions and to also help reduce the effort for application [17]. They are not standardized, thus indicators, indices, system boundaries, depth and focus of the analysis must be chosen individually. Examples of MCDA approaches include, but are not limited to: Analytical Hierarchy/Network Process (AHP/ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Grey Relational Analysis (GRA), ELimination Et Choice Translating Reality (ELECTRE), Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE) and Fuzzy Logic approaches [2].

The AHP is based on creating a ranking – i.e. a hierarchy of elements – by pairwise comparison. This ranking is either used directly as a comparative assessment of alternatives, or to deduce weights of the considered elements [4]. The ANP is the generalization of the AHP. It is suited to problems in which elements are interconnected by complex relationships, thus a network of elements can be investigated [2].

The general idea of TOPSIS is that the optimal alternative has the highest score for all the criteria taken into consideration. Thus, the alternative with the shortest geometrical distance to the ideal solution and simultaneously the largest geometrical distance to the least favorable solution is deemed the most advantageous choice. The ideal solution is comprised of the solutions containing the maximum scores in all criteria, and respectively the worst solutions are comprised of the minimum scores [7].

The idea of GRA is similar to TOPSIS but, in addition to looking at the geometrical distances between the ideal and least favorable solutions, error intervals and other parameters are included as well. Multiple assessment criteria are evaluated simultaneously. Due to complex mathematical calculation rules, the definition of the assessment formula is time and process intensive [4,7].

The ELECTRE method is characterized by a two-step approach. Firstly, hierarchical relationships between the alternatives being considered are constructed. The focus here is on dominance between alternatives. Secondly, graphs are created based on pairwise comparisons, concordance and discordance indices, as well as threshold values. These graphs are then used to determine the final ranking of the alternatives. The method is suitable for decision-making situations with few criteria, but multiple alternatives. Both qualitative and quantitative criteria can be included. Due to the complexity of the assessment process, one or more advantageous alternatives are chosen [2,7].

PROMETHEE is also based on a ranking principle, but it is less complex and easier to use than ELECTRE. The method is based on weighted hierarchical relationships related to inputs and outputs of the considered system. Similar to other methods, the alternatives are compared pairwise. However, in addition to simply using preferences to compare alternatives, distances between alternatives are also considered [7].

Fuzzy Logic or Fuzzy Set Theory is based on the assumption that objects can be attributed to more than one set, the attribution is therefore fuzzy. It emulates the human mind, which extracts qualitative information from numerical, categorical or linguistic data and rates, summarizes and processes this information to make decisions and assessments [18]. Fuzzy Logic provides mathematical tools with the ability to process crisp as well as fuzzy inputs in order to create crisp outputs. Due to the complexity of sustainability, not all indicators can be measured quantitatively and thus have to be estimated or assigned qualitative values. This uncertainty and subjectivity, i.e. fuzziness of inputs, can be processed in a fuzzy system to provide a crisp, absolute output value [18].

Existing approaches to sustainability assessment provide several starting points for improvement and optimization. For instance, LCA only looks at quantitative indicators of the ecological dimension. The combination with LCC and S-LCA is an initial step towards an integrated assessment in the form of LCSA, though the costs of data acquisition, consolidation and processing are high [16]. In classical methods, the sustainability dimensions are considered separately, which implies a trade-off between different indicators and dimensions [3]. For an integrated assessment, all three dimensions, their intersections and relationships must be considered equally [13]. In some applications, certain life cycle phases are omitted. By including aspects of the entire life cycle, a more complete image of sustainability is provided [6]. Due to subjective or uncertain inputs, results of the assessment can be distorted [2]. By choosing an approach that is equipped to process these uncertainties, more reliable assessment results are generated [18]. Methods like GRA, ELECTRE or PROMETHEE are characterized by complex mathematical operations and thus elaborate assessment procedures [7]. By limiting the effort of those carrying out the assessment, the more attractive the sustainability assessment becomes. All the methods described provide assessment results as complex as the assessment process itself. Easily understandable visualization techniques facilitate the interpretation of results [19]. Based on these aspects, which are described in literature, seven requirements are deduced for creating a holistic method for sustainability assessments of RET. They are summarized in Table I.

<table>
<thead>
<tr>
<th>No.</th>
<th>Requirement</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Consideration of all sustainability dimensions</td>
<td>R1</td>
</tr>
<tr>
<td>R2</td>
<td>Separate and aggregated evaluation of sustainability dimensions</td>
<td>R2</td>
</tr>
<tr>
<td>R3</td>
<td>Inclusion of the entire life cycle</td>
<td>R3</td>
</tr>
<tr>
<td>R4</td>
<td>Inclusion of quantitative and qualitative aspects of sustainability</td>
<td>R4</td>
</tr>
<tr>
<td>R5</td>
<td>Processing of uncertainties and subjectivity of inputs and calculations</td>
<td>R5</td>
</tr>
<tr>
<td>R6</td>
<td>Balancing level of detail and effort of data procurement, consolidation and processing</td>
<td>R6</td>
</tr>
<tr>
<td>R7</td>
<td>Structured, clear and understandable visualization of results</td>
<td>R7</td>
</tr>
</tbody>
</table>
III. PROPOSED METHOD FOR SUSTAINABILITY ASSESSMENT

The proposed Fuzzy Logic Approach for Sustainability Assessment Based on the Integrative Sustainability Triangle (Fuzzy-IST) is based on the combination of a multi-stage fuzzy logic approach, which aggregates Basic Sustainability Indicators (BSI) into Sustainability Dimension Indices (SDI) and then into a GSI, with the IST as a tool for the systematization of indicators and a visualization of the results. The approach is presented in Figure 3 and further illustrated in the following sections.

The first step is the selection of appropriate BSI, which are then systemized in a simplified IST to balance out the different sustainability dimensions. The simplification of the IST is done by combining the social/ ecological/ economic with mainly social/ ecological/ economic fields (see Figure 5) in order to facilitate the allocation of indicators. The indicator set is variable in terms of number and type of indicators used. Depending on the application, requirements of the analysis and data availability, the BSI are selected based on theories, empirical analysis, pragmatism or a combination of these factors [14].

In step two, the indicators are normalized to facilitate the comparability and processing of BSI with different units. For normalization, three different equations are used. Equation (1) is applied if a low input value is seen as advantageous. For an advantageous high value, (2) is used whilst (3) is applied if a low input value is seen as advantageous.

For an input value of BSI representing sustainability, the amount of calculations, as facts are better represented. The same goes for the number of aggregation steps, i.e. the number of aggregation steps, decreases with an interval of the scale for each indicator is naturally [0,1]. For each scale, there are several discrete sets that are described in linguistic terms and overlapping triangular membership functions. The terms and membership functions indicate the extent to which the input value is attributed to the discrete sets. The overlap between membership functions represents the attribution of input values to two adjacent sets. An example is given in Figure 4. Here, the discrete sets are represented by the linguistic terms very bad, bad, neutral, good and very good on a scale from 0 to 1.

In step four, the rule base is defined. It specifies the aggregation of indicators and consists of simple IF-THEN rules, which connect the linguistic variables of the indicators to one another. The rules consist of two parts: the premise (IF) and the conclusion (THEN). In the Fuzzy-IST, in each aggregation step (j), (n_j) indicators are combined. Therefore, each premise consists of (n_j) conditions, i.e. the assignment of input values to linguistic variables. The conditions are combined using operators of classic set theory, such as conjunction (AND) and adjunction (OR). The number of rules (S_k) for all aggregation steps (k) is related to the number of discrete sets described in linguistic terms (m_j) and the number of aggregated indicators (n_j) per step [18]. If the number of discrete sets is the same for all indicators of an aggregation step, the total number of rules is calculated as in (4).

\[ S_k = \sum_{j=1}^{k} m_j^{n_j} \]

The number of rules increases with all three parameters, thus contributing to the rule explosion – i.e. the exponential growth of the rule base [18]. The level of detail increases with an increasing number of discrete sets for one aggregation step as facts are better represented. The same goes for the number of BSI representing sustainability. The amount of calculations, i.e. the number of aggregation steps, decreases with an
increasing number of indicators being aggregated at once. In order to keep the number of rules controllable whilst maintaining a satisfactory level of detail, a trade-off has to be made between the three parameters ($m_j$, $n_j$, $k$) [18].

The general form of a rule ($R_p$) using conjunction is illustrated in (5). The linguistic Term ($T_{i,p}$) of the indicator ($i$) is assigned to the normalized input value ($x_i$). The conclusion comprises the linguistic term ($T_{n+1,p}$) and the corresponding output value ($x_{n+1}$) of the aggregated (sub-)index ($n+1$). For adjunction, the AND-operator in has to be exchanged with OR.

$$R_p: IF \left( x_i \ is \ T_{i,p} \right) \ AND \ ... \ AND \ \left( x_n \ is \ T_{n,p} \right), \ THEN \ \left( x_{n+1} \ is \ T_{n+1,p} \right).$$

(5)

In the Fuzzy-IST, as a trade-off between the level of detail and the effort required for calculation, indicators and indices are aggregated in sets of two. Thus, the rule base for each aggregation step can be represented in a compact matrix form, as shown in Table II with the top value in each cell being ($T_{n+1,p}$) and the bottom value being ($x_{n+1}$).

The first sub-step of step five is the fuzzification of input values, i.e. the translation of crisp inputs into linguistic terms using defined membership functions. A normalized input value ($x_i$) is assigned to the linguistic term ($T_{i,p}$) with a membership grade of ($\mu_{T_{i,p}}$)). The membership grade is a real number in the interval [0,1] (see Figure 4).

The following sub-step is the fuzzy inference, i.e. the actual calculation for the aggregation of BSI based on the rule base. In the Fuzzy-IST, the Takagi-Sugeno-Kang (TSK) inference is used. A hierarchical network of TSK fuzzy systems is monotonic across all aggregation stages, i.e. changes in lower stages lead to corresponding changes in upper stages [18]. For rules using conjunction, the algebraic product rule from (6) is used. For adjunction, an algebraic sum rule, as illustrated in (7), is used. If more than one rule assigns the same linguistic variable ($T$) to the input value ($x_{n+1}$), the membership grade ($\mu_{T_{n+1,p}}$) is calculated using (8).

$$\mu_{n+1,p}(x_{n+1}) = \prod_{i=1}^{n} \mu_{i,p}(x_i)$$

(6)

$$\mu_{n+1,p}(x_{n+1}) = 1 - \prod_{i=1}^{n} (1 - \mu_{i,p}(x_i))$$

(7)

In the third sub-step of step 5, the defuzzification, crisp outputs are calculated from the membership values of the aggregated inputs. In the Fuzzy-IST, Singleton defuzzification is used. It provides clear and crisp output values with minimal calculation effort [18]. The output value ($x_{n+1}$) is calculated as in (9), while ($A_T$) is the numerical value of the linguistic variable ($T$) at ($\mu_T = 1$).

$$x_{n+1} = \frac{\sum_{p: T \in T_{n+1}} \mu_{T_{n+1,p}}(x_{n+1})}{\sum_{T} \mu_{T}(x_{n+1})}$$

(9)

All sub-steps of step five are repeated throughout the multistage hierarchical aggregation, from BSI, to SDI, to GSI, with the outputs of each stage being used as inputs for the next stage (see Figure 2 and Figure 3).

The sixth step is the comprehensive visualization of the results based on a simplified IST (see Figure 5). The fields representing the sustainability dimensions and their intersections are color coded (red – yellow – green) based on their calculated sustainability values. Low values (below 0.5)

TABLE II. RULE BASE MATRIX FOR AGGREGATION OF TWO INPUTS

<table>
<thead>
<tr>
<th>Rule base</th>
<th>Input B</th>
<th>VB</th>
<th>B</th>
<th>N</th>
<th>G</th>
<th>VG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VB</td>
<td>B VB</td>
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<td>0.25</td>
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<tr>
<td></td>
<td>B</td>
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<td>N</td>
<td>G</td>
</tr>
<tr>
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<td>0.75</td>
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<td>VG</td>
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<td>VG</td>
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are coded red—orange—dark yellow and represent a negative influence on the sustainability value of the dimension being considered. The lower the calculated value, the more negative the influence on overall sustainability. High values (above 0.5) are coded light yellow—light green—dark green and represent a positive influence on the sustainability value of the dimension. The higher the calculated value, the more positive the influence on overall sustainability. Thus, advantageous and disadvantageous dimensions are easily identifiable and recommendations for actions can be easily deduced. The color-coded circle in the top-left corner (see Figure 5) represents the overall sustainability—i.e. the value of the GSI.

IV. RESULTS, DISCUSSION AND CONCLUSION

For the development of the new method, requirements (R1–R7) were determined based on the literature (see Table I). By systemizing the BSI in the IST, all sustainability dimensions and their intersections are included in the assessment (R1). By using stepwise aggregation to create SDI and finally a GSI and representing the results of those calculations in the color-coded IST, all dimensions are made evaluable (R2). The definition phase for BSI is used to include aspects throughout the entire life cycle of the object under investigation (R3). By using a fuzzy logic approach, quantitative, as well as qualitative indicators are included, and uncertainties and subjectivity are made processible (R4, R5). The effort required for data acquisition depends on the availability of data and the expertise of the user. The level of detail depends on the quality of the data, scales and membership functions (R6) [18]. The representation of results in the color-coded IST provides a structured, clear and understandable visualization of the results (R7).

The Fuzzy-IST has been applied to wind energy [20]. The exemplary sustainability assessment leads to an overall neutral classification result for the wind power plant being considered as it showed strengths and weaknesses in the various dimensions. By making a trade-off between the number of aggregation steps and the number of rules in the rule base—i.e. a trade-off between level of detail and the complexity of calculations—information could be lost during aggregation. A starting point for further investigation is research into the influence the number of aggregation steps and/or the number of linguistic terms has on the results. The current model as applied in [20] does not consider interdependencies or weights of BSI and SDI. In order to fully integrate all sustainability dimensions and life cycle phases, further research into these aspects is needed. The applicability for other RET also needs to be investigated.

All in all, the Fuzzy-IST is suitable for investigating the positive and negative impacts of RET throughout their life cycle and in doing so overcome deficits present in other approaches to sustainability assessment. The visualization of the results and corresponding numerical values provide comprehensive decision-making support. However, further research is needed in order to further improve and validate the Fuzzy-IST.

REFERENCES

Research on Electrical Brake of A Series-parallel Hybrid Electric Vehicle

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Abstract—For the sake of high-efficiency energy recycling and brake security for series-parallel hybrid electric vehicle, an integrated brake system with an electric consuming brake subsystem and advanced strategy is proposed. The brake processes in different brake conditions are analyzed. A brake control strategy relying on the brake condition is applied in the series-parallel hybrid electric vehicle. In view of the complexity and dynamic characteristics, a coupled whole vehicle model which combined the driveline model and the thermal management system model is proposed to study the energy flow and utilization in the different electrical brake processes. A simulation of the whole vehicle under an UDDS driving cycle is studied. According to the simulation result, the integrated brake system can effectively protect the battery. With this subsystem, the electrical brake and electrical-mechanical combined brake can still be used safely in high battery SOC and high voltage conditions. According to that, the energy generating from the brake process can be fully utilized and the lifetime of the mechanical brake device can be prolonged. In view of the complexity and dynamic characteristics, an integrated simulation analysis method based on a mechanical-electrical-thermal coupled simulation model is proposed to study the energy flow and utilization in the electrical brake process.

Keywords—electrical brake; brake control strategy; series-parallel hybrid electric vehicle

I. INTRODUCTION

As the global issues of energy scarcity and environmental pollution get more and more remarkable, the research of the hybrid electric vehicle, which has the advantages of both electric vehicles and traditional internal combustion vehicles, has become the hot point in the vehicle research field at present. The powertrain of hybrid electric vehicle is incredibly complex, with mechanical, electrical and thermal interactions between the internal combustion engine, gearboxes, electrical machines, power electronics, controlling systems and so on. The brake energy recycling is a typical characteristic of hybrid electric vehicle, which can affect both the security and energy saving of the whole vehicle. Therefore, there are a lot of researches have been pursued on the brake energy recycling, ranging from cooperative control[1-4] of regenerative brake and friction brake to the dynamic performance analysis in brake process[5-7]. However, the common trait of these existing hybrid electric vehicle brake control strategies is to use mechanical friction brake instead of electrical brake completely in the high-intensity brake or high battery state of charge (SOC) and high battery voltage conditions in order to ensure the safety of the driving and charging. That results in a kind of waste of brake energy as well as reducing the working lifetime of the mechanical brake. In this paper, a unique integrated brake system with adaptive control strategy is applied to a series-parallel hybrid electric vehicle. This brake system contains an electric consuming brake subsystem which can effectively protect the battery. With this subsystem, the electrical brake and electrical-mechanical combined brake can still be used safely in high battery SOC and high voltage conditions. According to that, the energy generating from the brake process can be fully utilized and the lifetime of the mechanical brake device can be prolonged. In view of the complexity and dynamic characteristics, an integrated simulation analysis method based on a mechanical-electrical-thermal coupled simulation model is proposed to study the energy flow and utilization in the electrical brake process.
II. BRAKE PROCESS ANALYSIS

A. Brake schematic of Series-parallel hybrid electric vehicle

Depending on the operating conditions and work processes, the electrical brake of the series-parallel hybrid electric vehicle can be divided into two forms, regenerative brake and electric consuming brake. In the regenerative brake process, the electricity generated from the brake process is used to charge the battery. The regenerative brake strength is affected by many factors, such as the maximum allowed working current of motor in generating mode, the maximum charging current and voltage of battery and so on. The electric consuming brake is applied in the high intensity brake process or continuous brake process. In these situations, the recycled electrical brake energy could not be fully absorbed because of the capability limitation of the energy storing components such as battery. Under this circumstance, the brake resistor belonged to the electric consuming brake subsystem should be applied to consume and transfer the surplus energy in order to assure the safety and reliability of vehicle. The schematic of electrical brake process and energy flow of this series-parallel hybrid electric vehicle are shown in Figure 1. According to the principles of optimum of energy conservation, the minimizing of the wear of mechanical brake components and the maximum protection of the battery, the brake priority can be defined in the following stages. The first brake stage is regenerative brake. The second one is regenerative brake combined with electric consuming brake. The third one is electrical-mechanical combined brake. According to the vehicle operating state, the proper selection of electrical brake modes can greatly reduce the usage intensity and frequency of mechanical friction brake components and increase their working lifetime and operation reliability.

![Figure 1. The schematic of the electrical brake of series-parallel hybrid electric vehicle.](image)

B. Operation of electric consuming brake

Based on modular design method, the electric consuming cooling system related to the electric consuming brake subsystem is designed as part of thermal management system. The schematic of thermal management system under electric consuming brake is shown as Figure 2. The red parts in the picture are the main heat source components in the brake process. In this self-adaptive thermal management system, electric pump and electric fan which can be continuous speed adjusted are applied in light of the system flexible control. Then the active-adjust of the thermal management system can be easily realized.

![Figure 2. The schematic of the thermal management system with electric consuming system in electric consuming brake process.](image)

In the brake process, when the voltage and SOC of the battery reach to their maximum limitations, the vehicle works in its electric consuming brake mode. In this situation, integrated brake system opens the operating switch to active the brake resistor. Then the brake resistor starts to be charged. The temperature of the brake resistor begins to go up. And then the electric consuming brake cooling system goes to work as the temperature going up. Before this process, the bus voltage of the vehicle should be checked firstly. Then the signal is sent to the integrated controller of the vehicle through the voltage transducer. Compared to the estimated voltage maximum limitation, the integrator unit of the integrated controller should plus one continuously when the measured voltage value is bigger than the calculation value. When the accumulative value exceeds the set value, the brake resistor is active.

C. Calculation of the vehicle brake process

In the vehicle brake process, the motor works in its generating mode. The kinetic of the vehicle is transferred to the electricity which is used to charge the battery in order to realize the energy recycling. Under this circumstance, the brake force generated by the motor can be calculated by the following formula.

\[
F_{\text{sm}} = i_i \tau_{\text{sm}} \eta_i \eta_t / r_w
\]  

(1)

\(F_{\text{sm}}\) is the brake force of the motor, \(\tau_{\text{sm}}\) is the brake torque of the motor, \(i_i\) is the ratio of the transmission, \(\eta_i\) is efficiency of the motor, \(\eta_t\) is the efficiency of the transmission, \(r_w\) is the wheel radius.

According to the following classic driving equation, the energy consumed in the driving or brake process can be calculated.
\[ E = \int P_i \, dt = \int F_i \, v \, dt \]  

(2)

\[ E \] is the energy consumed in the vehicle driving or brake process, \( P_i \) is the power consumed in the vehicle driving or brake process, \( F_i \) is the force required in the vehicle driving or brake process, \( v \) is velocity of the vehicle.

\[ F_v = \delta M \frac{dv}{dt} + F_r + F_i + F_f \]

(3)

\[ F_v \] is the required brake force of the whole vehicle, \( \delta \) is the equivalent mass of rotating parts, \( M \) is the mass of the whole vehicle, \( F_r \) is the rolling resistance, \( F_i \) is the aerodynamic resistance, \( F_f \) is the gradient resistance, \( g \) is the gravitational acceleration, \( f \) is the rolling resistance coefficient, \( \theta \) is the slope of road, \( \rho \) is the density of air, \( C_o \) is the air drag coefficient, \( A \) is the frontal area of vehicle.

D. Control strategy of electrical brake

According to the relative parameters of the series-parallel hybrid electric vehicle, we can acquire the maximum motor brake force and the maximum brake intensity of motor in its independent brake process. The motor could take part in brake all the time during the vehicle operation, because of the electric consuming brake system. When the initial vehicle brake velocity is in a certain speed range, the electrical brake can be used as its maximum brake intensity which the motor permits. When the brake velocity is smaller than some minimum velocity, the motor can’t join in the brake process because of the enormous damping of the electrical brake intensity. Under this circumstance, the mechanical brake work as prime brake.

When the motor brake force can’t fulfill the requirement that the vehicle actually needed, the electrical-mechanical combined brake need to be applied. On one side, the electrical brake motor is allowed to work with its maximum brake intensity. On the other side, the mechanical brake supplies the additional portion of the brake force needing to fulfill the totally brake pedal stroke. When the vehicle speed falls below a certain speed, the electrical brake can’t fulfill the basic work, due to damping of the intensity of electrical brake. Under this circumstance, the mechanical brake plays the major role to meet the brake strength requirement of brake pedal stroke. The maximum vehicle brake force is not only related to the brake vehicle velocity, but also limited by the mechanical brake device and the total brake power of the motor.

The specific electrical brake strategy can be achieved as following.

(1) Enter the battery SOC, the vehicle velocity, the deceleration motor characteristics and battery characteristics.

(2) Judge SOC and velocity, when velocity exceeds the minimum velocity, the electrical brake is active. Otherwise mechanical brake is applied. In the electrical brake process, when the SOC of the battery exceeds 0.8, electric consuming brake is active. The surplus electricity is input to the brake resistor, or else goes to the next step.

(3) Calculate the maximum battery charging powers which are separately limited by the maximum voltage and maximum current of the battery.

(4) Calculate the maximum brake force which the motor can provide and the required brake force of wheels by the vehicle velocity and the brake deceleration. When the maximum brake force which the motor can provide is bigger than the required brake force of wheels, vehicle brake force can be provided entirely by the motor. In this situation, the vehicle brake force is equal to the required brake force of wheels. Then calculate the motor recovery power under the circumstance. When the maximum brake force which the motor can provide is smaller than the required brake force of wheels, the electrical-mechanical combined brake should be applied in order to maintain the stability of the vehicle deceleration. In this situation, the motor provides its maximum brake force and the rest of the brake force provided by the mechanical brake. The vehicle brake force is equal to the sum of mechanical brake force and electrical brake force. Then calculate the recovery power of motor.

(5) Compare the recovery power of motor with the maximum charging power the battery permitted. When the recovery power of motor is smaller than the maximum charging power the battery permitted, the electricity can be charged into battery. Or else, the recovered energy needs to be charged into the brake resistor.

III. SIMULATION MODEL

According to the vehicle structure and schematic, a mechanical-electrical-thermal coupled model of a series-parallel hybrid electric vehicle combined with powertrain model and thermal management system model is proposed. According to the coupled model, the energy flow, energy distribution and heat characteristics of components in the different driving condition especially for the complex brake process can be studied.

A. The schematic of the series-parallel hybrid electric vehicle

The schematic of the series-parallel hybrid electric vehicle is illustrated in Figure 3. The hybrid power system of series-parallel hybrid electric vehicle includes the internal combustion engine, the motor A, the motor B, the planetary power coupling device and so on. The internal combustion engine is linked to the planet carrier, the motor A is linked to the sun gear, and the motor B is linked to the ring which is paralleled on the output shaft. Both the motor A and the motor B can operate as generators or driving motors. In the series-parallel hybrid electric vehicle, the engine power is split by the planetary power coupling device. Some of the engine power is transmitted to the output shaft as mechanical power. Some of the engine power is transmitted by the motor A to the motor B or battery as electrical power. The torques of the motor B and the planet ring are coupled.
on the output shaft, and power split and coupling are implemented by the planetary power coupling device.

![Figure 3. Schematic of series-parallel hybrid electric vehicle with planetary power coupling device.](image)

**B. The simulation model of the whole vehicle**

Based on the unique vehicle structure and schematic, a coupled vehicle model which combined the driveline model and the thermal management system model is applied in the study. The hybrid modeling method which combines experiment modeling and theory modeling is adopted. The vehicle forward dynamic driveline simulation model is built with Matlab/Simulink which is shown in Figure 4. The thermal management system model which contains dynamic dissipation calculation model, temperature rising calculation model and the control strategy are also built in details with Matlab/Simulink, which is shown partly in Figure 5. The thermal management system contains the electric consuming brake cooling subsystem which is related to the vehicle electric consuming brake process. According to the coupled model, the energy flow, energy distribution and heat characteristics of components under different driving condition can be studied in details, especially for the brake energy flow and storage in the brake process. The effectiveness of the unique brake system and brake control strategy can be estimated by the simulation.

![Figure 4. The dynamic simulation model of the whole vehicle](image)

**IV. ANALYSIS OF SIMULATION RESULTS**

In different vehicle driving conditions, the ratio of brake energy and total energy is different. In the simulation, an international general urban road driving cycle UDDS is applied. As shown in Figure 6, the maximum velocity is 91.2 km/h. The initial SOC of the battery is set to 0.7. The simulation results can be seen in Figure 7 to Figure 9. According to the UDDS driving cycle, the vehicle needs to start, stop, accelerate and brake frequently. The SOC of the battery always declines. In light of recycling energy of the electrical brake, the SOC changing curve goes up and down accordingly which is related to the charge-and-recharge process. During the driving cycle, the specific changing process of battery SOC is shown in Figure 7. In the driving cycle, the vary process of bus voltage can be seen in Figure 8. The changing process of bus current in the whole driving cycle is shown in Figure 9. The research results show that when the bus voltage is lower than current SOC corresponding voltage limit value, the bus current is always less than the corresponding current limit value. In view of the results, the bus voltage is set as the key control parameter to active the switching of different kinds of brake in the brake process. When the bus voltage value exceeds detection limit voltage, the electric consuming brake is activated. Under the circumstance, the energy generating from the motor is transferred to the brake resistor. In the simulation, the limitation value of the bus voltage is set to 620V.
There are four kinds of energy can be referred to study the energy flow of series-parallel hybrid electric vehicle in the UDDS driving cycle. They are vehicle driving energy, vehicle brake energy, vehicle brake recycle energy which is related to the electrical brake process and vehicle effective brake recycle energy. According the simulation, throughout the driving cycle, the drive energy of the vehicle is 76030.2KJ. The vehicle brake energy during all the brake processes is 36823.3KJ. In the whole driving cycle, the brake energy takes up 32.6% of the total energy consumption. In the most of the brake process, the electrical brake can be applied. The brake recycle energy takes up nearly 70% of the total brake energy, while the effective brake recycle energy takes up 26.3% of the total brake energy. Base on this analysis results, the electrical brake system is applied in most of the brake process. In the whole driving cycle, the recycle brake energy used to charge the battery takes up nearly one third of the total brake energy. While the other two thirds recycle brake energy is transferred to the electric consuming brake system which can be used to warm-up the engine, heat the cab and seat of the series-parallel hybrid electric vehicle in order to realize the maximum utilization of the vehicle energy. Simulation results show that the complex integrated brake system and control strategy are effective for the series-parallel hybrid electric vehicle. It not only can ensure the security of the vehicle driving and battery energy storage, but also can enhance the energy utilization and prolong the working lifetime of mechanical brake device in the brake process.

V. CONCLUSION

The complex integrated brake system with electric consuming brake subsystem and advanced strategy proposed in this paper can fulfill the various brake requirement of the series-parallel hybrid electric vehicle under different driving conditions. In view of the complexity and dynamic characteristics of the different brake conditions, an integrated simulation analysis method based on a coupled vehicle model which combined the driveline model and the thermal...
management system model is proposed to study the energy flow and utilization of the electrical brake. According to the simulation results under the UDDS driving cycle, the analysis method based on the coupled simulation model can be applied on the dynamic brake traits and energy distribution research for series-parallel hybrid electric vehicle feasibly and effectively.

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Numerical analysis and model-based control of energy recovery ventilator in HVAC system

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Abstract — In recent years, the energy conservation demand attracted much attention due to the depletion of energy resource and environmental impact by increasing energy consumption. In particular, heating, ventilation and air-conditioning (HVAC) systems in buildings is responsible for significant portion of global energy demand. Heat or energy recovery is one of the key energy-efficient technologies, which reveals to overcome the increase of energy consumption in building without reducing the indoor air quality. However, in the conventional heat recovery system, only the sensible heat was recovered, but the latent heat was ignored. In this work, a novel energy recovery ventilation (ERV) model is developed with semi-permeable membrane, and the performance of sensible and latent energy subject to tropical climate conditions is investigated by both numerical and experimental methods. The 3D ERV model is comprehensively studied first by CFD simulation for analysis of important parameters, such as velocity, temperature, humidity of supply and exhaust airflow. The CFD simulation results show that the sensible and latent effectiveness could be gained at 75% and 65% respectively. Moreover, preliminary experiment is also conducted to validate the simulation results for the impacts of ERV on energy consumption. The dynamic model of HVAC is then constructed and developed in Simulink. The model predictive control strategy for the control of temperature, humidity and CO2 level will be implemented in this model for optimization of ERV control integrated into the whole HVAC system to achieve much more energy saving.

Keywords—energy recovery ventilator; heat exchanger; indoor air quality; HVAC system; control

I. INTRODUCTION

Recently the global energy consumption steadily increases with a high rate as a consequence of economic development and population explosion [1]. This situation raises concerns about the depletion of energy resource and environmental issues. For tropical weather such as that in Singapore, the electricity consumption in HVAC system is a major energy part, accounting for 50% of the energy use in the building sector in Singapore [2]. In addition, to improve the indoor air quality (IAQ) in environment, the ventilation rate should be increased which significantly consumes the energy to condition the new fresh air. In particular, in hot and very humid climate, the energy for traditional cooling and dehumidifying fresh air accounts for 20–40% of total HVAC energy consumption, in which dehumidification process plays a major part [3] and causes the high energy loading on the energy system.

In order to address the problems of high energy requirement and the associated environmental concern, heat and energy recovery system is one of the sustainable technologies to decrease energy demand for HVAC system and to improve the indoor air quality significantly. In the conventional recovery technology for building applications, the sensible energy was recovered through heat transfer but the latent energy was ignored. Lately, with the development of membrane technology, Zhang et al. [4] proposed the membrane-based energy recovery ventilator (ERV), which has capability to exchange both sensible and latent heat from the exhaust air to pre-condition the outdoor fresh air through the heat transfer and moisture diffusion with high effectiveness. Zhang and Niu [5] conducted the simulation in the humid weather of Hong Kong and showed that the ERV achieved greater impact on energy saving than traditional heat recovery. Nasif et al. [6] conducted an experimental study to investigate the performance of an Z-shaped energy heat exchanger in term of both sensible and latent effectiveness. They found that the air conditioning system with this ERV saved energy of 4% and 8% respectively, compared with traditional air conditioning system in moderate climate and humid climate. Mardiana and Riffat [7] developed an energy recovery system, which utilized cellulose paper as the material for transferable core. The experimental investigation indicated that the efficiency of 66% and 59% was possible for sensible and latent effectiveness respectively. The recovered energy was obtained up to 167W at 3.0m/s air velocity.

Moreover, various control techniques and optimization strategies were implemented in building automation and control system. Due to various inherent advantages, the model predictive control (MPC) has emerged in building control system in recent years as a promising approach, which can deal with variety of disturbances to select an optimal set of actions. MPC control utilizes a system model with predictable action and the ability to handle constraints. The cost function of MPC control is designed to achieve multiple objectives [8].

The energy recovery technique is a sustainable solution to solve the problems in increasing energy consumption and indoor air quality. The MPC control algorithm is highlighted...
because of its advantages in dynamic model control. However, it was recognized that few studies were carried out for the recovery system in tropics climate. In addition, few researchers paid attention to control aspect, which is potential for considerable improvement in energy recovery device efficiency. As such, the objectives of this study are to investigate the performance of ERV in hot and humid tropical climates, and to develop an optimal control strategy for ERV, which is integrated into the whole building control system, in order to reduce the energy consumption and maximize the thermal comfort.

II. MATHEMATICAL MODELING OF HEAT EXCHANGER

Firstly, the performance of sensible and latent energy subject to tropical climate conditions is investigated by numerical methods. The 3D ERV model with semi-permeable membrane is comprehensively studied by Computational Fluid Dynamic (CFD) simulation to conduct the analysis of several important parameters, including the velocity, temperature, humidity of supply, and exhaust airflow, as shown in Fig. 1.

\[ \varepsilon_s = \frac{(T - T_s)}{(T - T_a)}, \quad \varepsilon_c = \frac{W - W_s}{W - W_a}, \quad \varepsilon_m = \frac{H - H_m}{H_m - H_a} \]  \( (1) \)

III. EXPERIMENTAL APPROACH

The experiment of ERV with counter-cross flow configuration is carried out. Temperature and humidity sensors are set up at 4 sides of the device. LabVIEW by National Instruments is used as a platform to collect, display and record data transmitted from the sensors employed in the experiment. Various outdoor conditions are simulated by operating a heater and humidifier to alter the temperature and humidity level of the outdoor environment. Physical parameters, such as the mass flow rates and efficiencies (sensible/latent/enthalpy), are evaluated, as illustrated in Fig. 2.

IV. CONCLUSIONS

Energy recovery is one of the key energy-efficient technologies, which reveals to overcome the increase of energy consumption in building, without reducing the indoor air quality. The CFD simulation results demonstrate that the sensible and latent effectiveness could be gained at 75% and 65% respectively. The preliminary experimental data show that the sensible and latent efficiencies are primarily dependent on the outdoor temperature and humidity ratio respectively. With the tropical climate, ERV has a great potential for significantly saving total energy consumption in building.

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Session 4: Sustainable Energy Technologies

The I-Term Influence in Simulating Hydraulics: A Study of Classical and Intelligent Control
(Authors: Michail Papoutsidakis, Eleni Symeonaki, Dimitrios Tseles)

New approach for the selection of technologically most appropriate variant of the water supply system
(Authors: Bojan Đurin, Lucija Nađ)

A Simplified and Automated Fault Current Estimation Approach for Grid-Connected Low-Voltage AC Microgrids

Consideration for Use of Traditional Structure to Designing for Flexible Modern Furniture through Lu Ban Lock
(Author: Li Ying)
Abstract — As a result of the constant evolution in industrial machinery, a greater demand for system accuracy and stability arises. Hydraulic systems compound a discrete number of dynamic parts which are used extensively in motion control applications. In order to determine the motion direction, these dynamic parts have to be controlled. This paper aims to assess the hydraulic actuation system performance by implementing various control methods, in Matlab / Simulink environment with Sim Hydraulics. The first step of the process was modeling the system, which is divided in a hydraulic part and a mechanical one. A classic and a fuzzy PID controller are designed. Moreover the design and implementation of a fuzzy PID controller self-tuning-parameter is described along with the rule structure of the controller. Next comparative estimations are performed based on the input and output system data. Finally conclusions derive from the usage of the I-term and its effect on the system’s behavior through the analysis of results obtained through this experimental project.

Keywords— PD, conventional PID, fuzzy PID controller simulation software

I. INTRODUCTION

Hydraulics are considered to be a significant part of extensive use in industry because of their characteristics such as high power, fast response and adequate positioning capability. The extent of hydraulic systems applications is wide and includes regions such as building construction, mining, materials test, injection molding, active suspension, fatigue testing, paper machines, flight simulation, ships and electromagnetic marine engineering, robotics and so on. The highest position, force or pressure performance, is essential in all these applications and so the use of a suitable controller is necessary in order to provide such behavior and improve this performance, as in [1], [2] and [3].

As approximately 90% of industrial loops make use of PID controllers they are considered to be the most frequently used in industry. A PID controller provides a control signal that depends on three terms and is given by the following equation where U(t) is the control signal and e(t) is the error signal which is the difference between the reference signal r(t) and the system output y(t). Kp, Ki and Kd are the proportional gain, the integral gain and the derivative gain respectively, like [4], [5] and [6]:

$$U(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(t)dt + K_d \frac{de(t)}{dt}$$

Kp, Ki and Kd are these parameters that have to be tuned and were experimentally defined at first. Proper modelling of the system to be controlled is a defining step in the design of the controller. The environment chosen to create the system model, which consists of a hydraulic and a mechanical part as well as the controller, is Matlab / Simulink using Sim Hydraulics. Most of industrial processes implement a wide, non-linear setup PID controller algorithm turning, in several cases, the classic PID controller to be less effective even though its conventional algorithm offers simplicity, stability, easy adjustment and high reliability, as in [7] and [8]. In order to manage this kind of problems adaptive control with neural network or Fuzzy logic control (FLC) was suggested as a more intelligent type of control which has resulted to be more effective for complex imprecise non-linear systems. Fuzzy-PD control aims on a stability equation which provides more stable and robust systems whereas fuzzy-PID controller improves the robustness and hybrid control of fuzzy and PID by combining the advantages of fuzzy and conventional, self-tuning fuzzy linear control. This paper introduces the results which derived by the comparison of different controllers in an ideal system, attempting to specify, which one provides the most optimal output.

II. SETUP OVERVIEW

Fig. 1 illustrates the architecture of the simulation designed in Simulink in which the flow of hydraulic fluid from a pump is controlled by a hydraulic valve to the diverse sides of a double-acting hydraulic cylinder.
The controller is attached to a directional valve allowing it to control the movement of the spool inside the valve and additionally hydraulic fluid is drawn from a reservoir (Hydraulic reference block). Moreover, a Pressure Relief Valve is required in order to control the pressure provided by the pump and a hydraulic fluid block is used for specifying the hydraulic fluid used in the circuit.

The cylinder of a hydraulic actuator is necessary to be attached to such a point in space so that it will remain stable. For this purpose a Mechanical translational reference block is used. The hydraulic cylinder is required to act against a dumper. Furthermore a scope is required so as to receive the extension and contraction of the cylinder as well as a PS-Simulink Converter in order to convert the physical signal to a Simulink one. A solver which allows the computation completion by executing a numerical method to solve the set of differential equations, is used in the simulation setup. In this project ode15s is used since it is highly recommended for physical systems. A step and a pulse generator are inserted as input to the valve.

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III. FUZZY PID CONTROLLER DESIGN

Fig. 2 illustrates generally the basic schematic structure of the fuzzy PID controller.

Fig. 3 and 4 illustrate the actual Simulink structure and the fuzzy sub-system respectively.
The self-tuning parameter fuzzy PID controller is based on a conventional PID controller which is similar to the one in Figure 1. The reference value of the stroke is the input and the actual stroke of the hydraulic cylinder is the output while the parameters $K_p$, $K_i$ and $K_d$ are integral, proportional and derivative coefficients of the PID controller. The stroke error $E(e)$ and the differential of the stroke error $EC(de/dt)$ are the fuzzy controller inputs. Mamdani model is applied for the fuzzy inference structure in order to acquire the fuzzy PID controller parameters. Initially one of the basic self-tuning PID principles is the transformation of the input variables into Fuzzy quantities by the membership functions, as illustrated in Fig. 5.

$$M(z) = \min\{m(\chi); m(\gamma)\}.$$  
$$K_p = K_{p\min} + M* K_p(E; EC) * (K_{p\max} - K_{p\min})$$  
$$K_i = K_{i\min} + M* K_i(E; EC) * (K_{i\max} - K_{i\min})$$  
$$K_d = K_{d\min} + M* K_d(E; EC) * (K_{d\max} - K_{d\min})$$

Where $M$ stands for the weight coefficient, $K_{p\max}$ and $K_{p\min}$ are the maximum and minimum limits for the proportional gain, $K_{i\max}$ and $K_{i\min}$ the maximum and minimum limits for the integral gain, and $K_{d\max}$ and $K_{d\min}$ the maximum and minimum limits for the derivational gain.

Table 2 contains collectively $3 \times 3 = 9$ rules for one controller output tuning which equals to a total of $3 \times 9 = 27$ rules as there are three outputs ($K_p$, $K_i$ and $K_d$).

Table 2. Fuzzy rules for PID parameters calculation

<table>
<thead>
<tr>
<th>Piston stroke error $E$</th>
<th>Differential of the piston stroke error $EC$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>$S/B/S$</td>
</tr>
<tr>
<td>$Z$</td>
<td>$S/B/M$</td>
</tr>
<tr>
<td>$P$</td>
<td>$M/S/B$</td>
</tr>
</tbody>
</table>

The references of the abbreviations are as follows:

N: Negative  
Z: Zero  
P: Positive  
S: Small  
M: Medium  
B: Big

Table 2 contains collectively $3 \times 3 = 9$ rules for one controller output tuning which equals to a total of $3 \times 9 = 27$ rules as there are three outputs ($K_p$, $K_i$ and $K_d$).
IV. SIMULATION OUTCOMES

Experimental research outcomes constituted the basis for the initial tuning of PID control. The gain coefficients applied on PID and fuzzy PID are $K_p=350$, $K_i=11$ and $K_d=30$ while on PD and fuzzy PD the coefficient $K_i=0$.

Comparisons were performed between the classic PID/PD controllers as well the self-tuning Fuzzy PID/PD ones. The Step and Pulse responses of the system are illustrated in the following Fig. 8 and Fig. 9.

The step and pulse responses of classic PD controller are illustrated in Fig. 10 and Fig. 11. The red line stands for the step.
or pulse input while the blue line stands for the response of the system. Comparatively to PID, the PD follows the input in an effective way excluding the overshoot side effect of PID.

The responses of the system for Fuzzy PID and Fuzzy PD are illustrated through Fig. 12 to Fig. 15. It is observed that through $3 \times 3 = 9$ rules on step input, PD Controller finalizes faster its position, whereas fuzzy PID needs rather long time to settle.

Figure 12. Step response of fuzzy PID

Figure 13. Pulse response of fuzzy PD

Figure 14. Step response of fuzzy PD

Figure 15. Pulse response of fuzzy PD

Although the pulse responses of the systems for both controllers are almost identical to PD ones, they appear to provide an optimum behavior regarding the aspect of stability.
V. CONCLUSION

The project presented in this paper focuses on the analysis of the I-term effects in a classic and an intelligent controller on a hydraulic cylinder stroke. It was demonstrated, by the method of simulation and measurement performed in Matlab / Simulink, that on an ideal mathematical model which is not affected by external influences of the real world, the system performs in a more effective way without the usage of the I term in the controller. Furthermore it was observed that the conventional PD and fuzzy PD control are far more adequate for these type of applications in terms of reliability and stability.

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New approach for the selection of technologically most appropriate variant of the water supply system

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Abstract - Experts and managers in the water supply sector are often challenged with a lot of different variants of obtained solutions for various types of water supply systems. Nowadays, in addition to meeting the technological and economic criteria, it is necessary to meet other criteria, such as environmental, social, political and other. Among other procedures, multi-criteria methods are used for the solution of such issues. This paper will present the use of the multi-criteria method Promethee for the case of technological criteria. The purpose of this is finding a technologically most appropriate variant of the observed water supply system, given that the resulting solution variants differ according to the size of certain parts. In addition, this paper explains the scientifically innovative and, in view of engineering, applicable methodology for dimensioning the sustainable urban water supply system driven by solar photovoltaic (PV) energy, which then becomes Energy Sustainable Urban Water Supply System (ESUWSS).

Keywords - water supply; solar photovoltaic energy; criteria; Promethee

I. INTRODUCTION WITH DESCRIPTION OF THE ANALYZED SYSTEM

The analyzed system consists of three main parts (Fig. 1). These are: PV plant - solar photovoltaic generator and inverter with corresponding equipment - subsystem PV, pumping station with related equipment - subsystem PS and reservoir - subsystem V. These subsystems make up an integrated technological system and are functionally interconnected.

Figure 1. Urban Water Supply System (UWSS) driven by solar photovoltaic (PV) energy

This system basically turns solar energy from the environment during solar radiation into electrical energy in the subsystem PV, which is used for pumping of water into the water reservoir. Solar energy is of stochastic nature in view of intensity and duration of solar radiation. Therefore, the role of water reservoir as a container of water, i.e. energy, in conjunction with possible electric energy production from the subsystem PV, is crucial in providing the continuity and safety of water supply. Therefore, the system must be appropriately planned and dimensioned, i.e. the methodology described in this paper must be applied. Given the scope and purpose of this study, the detailed procedures and terms for dimensioning individual parts of the system will not be explained, but they can be found in [1] and [2].

II. METHODOLOGY

A. Critical Period Method

Novelty or the difference between the previous ways of dimensioning and dimensioning using the CPM is that instead of one critical period which relates to the maximum daily consumption of water, the CPM considers three critical periods. In the case of using PV energy for UWSS, these critical periods are: critical period for sizing the subsystem PV (PV generator and inverter) $I_{PV(i)}^*$, critical period for sizing the subsystem PS (pumping station) $I_{PS(i)}^*$ and critical period for sizing the subsystem V (water reservoir) $I_{V(i)}^*$ [2]. This provides security of the operation of each subsystem, since the sizing is performed with respect to the critical period/periods of each subsystem, which allows operating integrity of the entire ESUWSS.

The first critical period $I_{PV(i)}^*$ is defined for determining sufficient power of subsystem PV $P_{el,PS}$, which will provide enough electric energy for pumping water into the reservoir every day of the analyzed year, in accordance with the regime of daily water consumption in a settlement. This is the period (periods) in which the difference $\Delta V_{PV(i)}$ between the daily required water for population needs $V_{dw(i)}$ and daily pumped
water $V_{PS(i)}$ is minimum for every day of the year with regard to the balancing period $t_b$:

$$\Delta V_{Ps(i)} = V_{PS(i)} - V_{daily(i)},$$

$i = 1, 2, ..., 365 \Rightarrow \min \Delta V_{Ps(1)} \Rightarrow t_{Ps(i)}^*$

(1)

where $\Delta V_{Ps(0)}$ is acceptable difference in practical application, which is normally 0.

The duration of daily solar radiation $T_{d(i)}$ determines the possible operating period of the pumping station. This introduces the second critical period (periods) $t_{Ps(i)}^*$ for determining the capacity or power of the pumping station. $t_{Ps(i)}^*$ is the critical period (periods) in which the relationship between the daily consumption of water in a settlement $V_{daily(i)}$ and duration of daily solar radiation $T_{d(i)}$ is minimum:

$$\max Q_{daily} = \frac{V_{daily(i)}}{T_{d(i)}} \Rightarrow t_{Ps(i)}^*$$

(2)

It is understood that adequate PV subsystem power $P_{el,PV}$ is provided, with respect to the corresponding critical period $t_{Ps(i)}^*$. Thus, in accordance with the rules of the profession, the capacity of the pumping station is determined that can pump the required quantity of water $Q_{max}(\text{m}^3/\text{h})$, which in fact represents the highest flow per hour during a typical year in the planning period.

The critical period (periods) $t_{Ps(i)}^*$ for determining the reservoir volume $V$ is the period in which maximum daily water consumption in a settlement $V_{daily(i)}$ for each day $i$ is maximum during the year, where the intensity of solar radiation $E_{d(i)}$ and its duration $T_{d(i)}$ is satisfactory, so that subsystem PV can produce sufficient electricity to drive the main pumping station. It is understood that adequate PV subsystem power $P_{el,PV}$ is provided with respect to the corresponding critical period $t_{Ps(i)}^*$ and sufficient subsystem PS capacity $Q_{PS}$, also with respect to the corresponding critical period $t_{Ps(i)}^*$:

$$\max V_{daily(i)} \Rightarrow t_{V(i)}^*$$

(3)

Each of the three critical periods is determined with regard to a certain balancing period (periods) $t_b$, i.e. equalization periods of the required and pumped water or equalization periods of the required and produced energy. The shortest possible balancing period $t_b$ is one day. When the balancing period $t_b$ is longer the solution is in principle safer, because longer balancing period reduces the impact of extreme low insolation $E$ on the required power of the subsystem PV, $P_{el,PV}$. In addition, the system is more efficient with regard to the possibility of using solar radiation, since the sum of the total available solar insolation is greater when $t_b$ is longer. Therefore, the solution is safer and more rational in view of dimensioning the subsystem PV. This means that the required water can be pumped with a lower installed power of the subsystem PV.

B. PROMETHEE

PROMETHEE is an outranking method for a finite set of alternative actions to be ranked and selected among criteria, which are often conflicting. PROMETHEE is also a quite simple ranking method in conception and application compared with the other methods for multi-criteria analysis [3]. Alternatives are evaluated according to different criteria, which have to be maximized or minimized. Determination of the weights is an important step in most multi-criteria methods. It is assumed that the decision-maker is able to weigh the criteria appropriately, at least when the number of criteria is not too large [4]. For each criterion, the preference function translates the difference between the evaluations obtained by two alternatives into a preference degree ranging from zero to one. The alternatives evaluated will be generated as a function of the balancing period length (number of days) $t_b$.

III. CASE STUDY WITH INPUT DATA

This paper presents a hypothetical example of a settlement with a population equivalent of 8970. The settlement is located on an island in the southern Mediterranean part of Croatia. It is in a hilly area of the island and has one water reservoir located at a ground elevation of 259 m above sea level. Water flows into the reservoir from the wet basin of the pump station. Water flows into the wet basin of the pump station by gravity from the spring. Total head of the pump station is 82.41 m. The water quality is satisfactory and does not need treatment. The positions of the basic facilities of the water supply system are shown in Fig. 2 (modified from [5]).

![Figure 2. Case study schematic layout](Image)

The analysis is conducted according to the presented methodology. Specific water consumption per capita $q_{sp}$ is 160 l per day. The daily water consumption pattern through the year is shown in Fig. 3 [1]. Hourly water consumption pattern [1] in the settlement is determined by the daily regime of consumption, as shown in Fig. 4.
For the considered location, the average pump head is $H_{PS} = 82.41\, \text{m}$, average efficiency of the inverter and motor pump unit is $\eta_{MPU} = 0.75$, cell temperature coefficient is $\alpha = 0.005\, \degree\text{C}^{-1}$ and temperature of the PV generator in Standard Test Condition is $T_0 = 25\, \degree\text{C}$. The average daily global radiation $E_{S(i)}$ and average daily insolation period $T_{S(i)}$ are shown in Fig. 5.

The average daily cell temperature $T_{cell(i)}$ and average daily ambient air temperature $T_{a(i)}$ are shown in Fig. 6 [1].

### IV. RESULTS AND DISCUSSION

Based on the given data, by applying Equations (1-3), critical periods for all subsystems have been determined (Tab. 1). Also, by applying the previously presented methodology, the required PV generator power $P^*_{el\, PV}$ and required reservoir volume $V^*_{op}$ are calculated (Tab. 2). The required capacities of pump station $Q^*_{PS}$ i.e. power of pump station $P^*_{PS}$ are calculated by using the value of pump efficiency $\eta_{PS} = 0.90$ [12].

<table>
<thead>
<tr>
<th>Balancing period $t_e$ (days)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical period (days in year) for subsystem PV $t^e_{Fel(i)}$</td>
<td>352</td>
<td>344-345</td>
<td>344-346</td>
<td>349-352</td>
<td>348-352</td>
</tr>
<tr>
<td>Critical period (days in year) for subsystem V $t^e_{Vopt(i)}$</td>
<td>244</td>
<td>244-245</td>
<td>243-245</td>
<td>243-246</td>
<td>242-246</td>
</tr>
<tr>
<td>Critical period (days in year) for subsystem PS $t^e_{PS(i)}$</td>
<td>352</td>
<td>344-345</td>
<td>344-346</td>
<td>344-347</td>
<td>343-347</td>
</tr>
</tbody>
</table>
The results obtained using the software package Promethee [6] are shown in Fig. 7. All three values of individual sub-systems, i.e. power $P^{*}_{el, PV}$, volume $V^*_{op}$ and power $P^*_{PS}$ have the same significance or weight. Also, maximization of all values of individual subsystems for all balancing periods was set as a necessary input condition. Variant 2 significantly stands out compared to the remaining variants, so that based on the above said, it is technologically the most appropriate variant.

### TABLE 2. Sizes of subsystems for different balancing periods

<table>
<thead>
<tr>
<th>Bal. periods $t_b$ (days)</th>
<th>Power $P^{*}_{el, PV}$ (kW)</th>
<th>Volume $V^*_{op}$ (m$^3$)</th>
<th>Power $P^*_{PS}$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>512.50</td>
<td>1100</td>
<td>106.00</td>
</tr>
<tr>
<td>2</td>
<td>477.82</td>
<td>1178</td>
<td>119.47</td>
</tr>
<tr>
<td>3</td>
<td>443.87</td>
<td>1271</td>
<td>111.39</td>
</tr>
<tr>
<td>4</td>
<td>419.80</td>
<td>1415</td>
<td>105.10</td>
</tr>
<tr>
<td>5</td>
<td>403.45</td>
<td>1513</td>
<td>99.71</td>
</tr>
</tbody>
</table>

The results obtained using the software package Promethee [6] are shown in Fig. 7. All three values of individual sub-systems, i.e. power $P^{*}_{el, PV}$, volume $V^*_{op}$ and power $P^*_{PS}$ have the same significance or weight. Also, maximization of all values of individual subsystems for all balancing periods was set as a necessary input condition.

### Figure 7. Results obtained by using of method Promethee

It can be seen that Variant 2 is the most favorable given the value of the indicators, followed by variants 3, 1, 4 and 5. Variant 2 significantly stands out compared to the remaining variants, so that based on the above said, it is technologically the most appropriate variant.

### V. CONCLUSION

This paper shows that the issue of selecting the technologically most appropriate variant of the water supply systems, taking into consideration a number of criteria, can only be solved by using one of the multi criteria methods. In this case, the multi criteria method Promethee was applied as one of the most suitable for solving various engineering problems. In any case, further research requires more detailed and complex analysis of the problem. This includes the use of other multi criteria methods, expansion of input criteria, sensitivity analysis of the change in importance/weight of individual parameters, and engaging a large number of experts from different fields in the expert group that defines and analyzes the multi-criteria analysis.

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A Simplified and Automated Fault Current Estimation Approach for Grid-Connected Low-Voltage AC Microgrids

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Abstract—For a grid-connected AC microgrid (MG), when a fault occurs at the microgrid, adaptive overcurrent (OC) or directional overcurrent (DOC) relays must be activated as fast as possible to protect all distributed generation (DG) units and loads. Fault currents inside the grid-connected AC microgrid can be significantly varied because fault current contributions from the main grid and DG units are different depending on various fault locations, fault types, and high penetration of inverter-based distributed generators (IBDGs) and rotating-based distributed generators (RBDGs) in the microgrid. A traditional fault analysis method cannot be applicable for AC microgrids with the presence of both rotating-based distributed generators and inverter-based distributed generators. Therefore, this paper proposes a simplified and automated fault current estimation approach for grid-connected AC microgrids, which is effective to quickly and accurately calculate fault current contributions from IBDGs and RBDGs and the grid fault current contribution to any faulted sections in the microgrid. This simplified and automated fault current calculation approach is mainly focused on grid-connected and small-sized low-voltage (LV) AC microgrids with the support of communication system. Under the grid-connected operation mode of the MG, fault tripping current thresholds of adaptive OC/DOC relays can be properly adjusted by the proposed fault analysis method. In particular, relying on fault current distribution coefficients of IBDGs, RBDGs, and the utility grid, pick-up currents of the adaptive OC/DOC relays in the LV AC microgrid are instantly and accurately self-adjusted according to different MG configurations as well as the operation status of DG units during the grid-connected mode.

Index Terms—AC Microgrids, Fault Current Analysis, Microgrid Protection, and Protective Relays

I. INTRODUCTION

A. Motivation and Literature Review

To enhance reliability and stability of the microgrid operation, peer-to-peer (P2P) and plug-and-play (P&P) characteristics are applied for each DG unit of the microgrid [1,2]. The P2P characteristic defines that there are no electrical components that are critical for the microgrid operation. In other words, the microgrid operation is continuous irrespective of connecting/disconnecting any DG units or energy storage systems. The P&P characteristic defines that a DG unit or an energy storage device can be placed at any point in the microgrid without redesigning a MG control system. The plug-and-play concept enables high penetration of distributed generators to anywhere in the microgrid. However, the peer-to-peer and plug-and-play characteristics significantly impact on the MG protection system. In particular, the peer-to-peer characteristic causes a major change in fault current values, which can lead to under-reaching/over-reaching of traditional overcurrent (OC) protection solutions, blinding of the OC protection, or sympathetic tripping of the OC protection [3]. For example, rotating-based distributed generators (RBDGs) produce high fault currents so that the OC/DOC relays are instantly activated to protect the microgrid. On the other hand, inverter-based distributed generators (IBDGs) limit their output fault currents, so the OC/DOC relays have certain difficulties in differentiating between overload and fault currents in the microgrid [4,5]. Moreover, variable fault currents may result in the protection mis-coordination among conventional OC relays, fuses, and reclosers [6,7]. In addition, the plug-and-play characteristic of the microgrid causes bi-directional power flows, which can lead to the re-operation of protective devices. The coordination among current-based protection devices can be disrupted because most of them are non-directional protection devices [3].

Microgrid protective relays must be designed to operate in both the grid-connected and islanded modes. At the islanded operation mode of the microgrid, the total fault current is significantly limited due to fault behaviours of inverter-interfaced DGs, which cannot be high enough to activate traditional overcurrent relays [4]. At the grid-connected operation mode, fault currents inside the microgrid can be greatly varied because of different fault current contributions from the main grid and various DG units. Fault current values
depend on various fault locations, fault types, and penetration levels of inverter-based distributed generators and rotating-based distributed generators in the microgrid. This situation can cause detrimental effects of sympathetic tripping, blinding of the overcurrent protection, over-reaching/under-reaching of overcurrent relays, and the selectivity loss of a standard overcurrent protection system [8].

From aforementioned microgrid protection challenges, although directional overcurrent and overcurrent relays are more appropriate to protect AC microgrids at the grid-connected operation mode than that at the islanded operation mode, the significant change in fault currents caused by fault locations, fault types, the penetration of IBDGs and RBDGs, and microgrid configurations can lead to the mis-operation of the relays. A traditional fault current analysis method is also inaccurate to be used for AC microgrids because of fault behaviours of IBDGs [4]. In order to accurately estimate fault current values in the RBDD and IBDG-contained AC microgrid for setting of the overcurrent relays, several different solutions are recently proposed in the literature [9-26]. In [9], the authors proposed a method to modify the conventional fault analysis methods such that fault current contribution of IBDGs can be considered. Although the proposed approach can accurately estimate IBDG fault currents at balanced and unbalanced fault conditions, it cannot be generally covered all different system configurations as well as different types of IBDGs, can be time-consuming, and needs to be re-calculated depending on the operation status of DG units (i.e., connecting/disconnecting the DG units to the system). References [10-12] presented fault models of inverter-interfaced distributed generation units and their application in fault current analysis of the system. Reference [10] shows that the inverter only supplies the positive-sequence fault current; and negative- and zero-sequence impedances of the microgrid seen from a faulted point can be reduced to an equivalent impedance. References [11,12] focus on fault response of grid-connected inverter-dominated distribution networks. They use the Gauss-Seidel load flow method which can be time-consuming and less recommended for weakly meshed low-voltage AC microgrids. On the other hand, references [13,14] proposed an adaptive fault current calculation algorithm based on a Newton-Raphson iterative method with a modified sequence-component network connection. Fault response of IBDGs is controlled to only inject positive-sequence fault currents into the system with a pre-determined value (at mostly less than 2.0p.u [15]). Due to employment of low-pass filters, the negative-sequence current component can be filtered out. Furthermore, the zero-sequence current component can be eliminated by three-phase three-leg inverter based distribution generators or the connection of IBDGs to grounded-wye (Y0)/delta (∆) isolation transformers. However, in [13,14], the iterative computation in fault current analysis is non-flexible and quickly non-adaptable to plug-and-play and peer-to-peer characteristics of microgrids with the intermittent operation of distributed energy resources (e.g., wind-turbine (WT) and photovoltaic (PV) generation systems).

In addition, reference [16] presented a backward/forward sweep algorithm to calculate the steady-state fault current contribution of IBDGs when connected to weakly meshed radial distribution networks. In [17,18], a microgrid fault analysis algorithm using a modified impedance matrix is proposed. Two relationship matrices, the bus injection to branch current matrix and the branch current to bus voltage mismatch matrix, are developed to achieve power flow solutions. However, not only the building of the proposed impedance matrix is time-consuming, but also the extra calculation time of fault currents is inevitable. References [19-25] presented steady-state sequence-component frame models of distributed energy resources (including both IBDGs and RBDGs) for power flow analysis as well as fault current calculation of microgrids and active distribution systems. In [19-21,24,25], three-wire and/or four-wire three-phase distribution networks, positive-/negative-/zero-sequence models of IBDGs and RBDGs, three-wire and four-wire voltage-sourced converter (VSC) configurations, unbalanced current mitigation of VSC, negative-sequence fault current blocking of VSC, and the operating limits of the interface VSC (e.g., phase current limit, modulation index limit, and PCC bus voltage limit), PCC are all considered for power-flow algorithms or fault-current analysis in the system. In [22], steady-state, fundamental-frequency, and closed-form models of distributed generators interfaced by voltage-sourced AC-DC-AC converters and AC-AC matrix converters are studied. These DG models are applied to a two-step power-flow analysis of a converter-dominated microgrid, under both grid-connected and islanded operation modes. Moreover, reference [23] showed a novel three-phase AC-DC-AC converter model that contains three single-phase, wye-connected rectifiers and inverters. This model can be applicable to unbalanced/balanced microgrids in order to implement power-flow analysis or fault analysis. In general, references [19-23] mainly focus on active and radial distribution networks or distribution voltage (medium-voltage) microgrids to develop power-flow analysis models as well as fault-current analysis, while fault analysis of low-voltage AC microgrids has not been comprehensively considered. In [26], a fault current estimation method for the sufficiently small-scale LV microgrids is proposed. This fault calculation method only focuses on balanced faults and is developed for radial electrical systems. Besides that, fault behaviours of IBDGs are assumed to only supply positive-sequence fault currents to a faulted section in the microgrid. Therefore, it is needed to study further on asymmetrical fault current estimation methods for LVAC microgrids (with weakly non-radial LV AC microgrids such as ring or meshed microgrids). Additionally, negative-/zero-sequence fault current injection of IBDGs into the faulted section in the microgrid should be taken into account.

B. Main Contribution and Structure of the Paper

The objective of this paper is to introduce a simplified and automated fault current estimation approach for grid-connected low-voltage AC microgrids. The proposed approach can quickly and accurately calculate fault current contributions from IBDGs and RBDGs and the grid fault current contribution to various faulted sections in the microgrid with the support of communication system.
Advantages of the proposed fault analysis approach are to fill up research gaps from the literature survey [9-26], particularly as the following:

1) Be applicable to different configurations of low-voltage AC microgrids (e.g., weakly non-radial/radial microgrids) as well as different fault behaviours of IBDGs (e.g., IBDGs only inject positive-sequence fault currents, or other IBDGs inject negative-/zero-sequence fault currents into the microgrid);

2) To simplify fault analysis of grid-connected LVAC microgrids by calculating fault current coefficients (or current distribution factors) of any DG types impacting on adaptive OC/DOC relays under different fault conditions (i.e., different faulted sections, different fault types) inside the microgrid;

3) To correspond with the changing operation of microgrids (e.g., different penetration levels of IBDGs and RBDGs, the intermittent operation status of DG units), fault currents can be automatically, quickly, and accurately calculated by a central microgrid control system (CMCS) communicating with all DG units and protective relays.

4) Under the grid-connected operation mode of the LVAC microgrid, fault tripping current thresholds of adaptive OC/DOC relays can be properly self-adjusted due to the proposed fault analysis. In particular, relying on fault current distribution factors of IBDGs, RBDGs, and the utility grid, pick-up currents of the adaptive OC/DOC relays are instantly and accurately self-adjusted according to various microgrid configurations as well as the operation status of the DG units.

5) For small-scale low-voltage microgrids, building of the sequence impedance matrix is not complex and time-consuming. The sequence impedance matrix is needed to calculate fault current coefficients of RBDGs and the utility grid impacting on all protective relays in the MG.

The structure of this paper is as follows: Section II presents a simplified and automated (SA) fault current estimation approach for grid-connected LVAC microgrids. Section III shows application of the SA fault analysis approach to a multi-grounded 380V AC-microgrid fault protection system under the grid-connected operation mode. It is worth noting that this fault protection scheme uses adaptive OC/DOC relays as primary protection of the microgrid. Section IV provides several selected simulation results to validate the proposed SA fault current calculation algorithm for grid-connected AC microgrids. Finally, Section V gives the conclusions.

II. A SIMPLIFIED AND AUTOMATED FAULT CURRENT ESTIMATION APPROACH FOR GRID-CONNECTED LVAC MGs

Microgrid topologies are mostly flexible and connections of DG units, loads, and storage devices in the microgrid are dynamic. The operating conditions of DG units (e.g., PV or WT generation units) can be intermittent due to weather effects. To get high reliability and stability of the MG operation, a central microgrid control system (CMCS) is required to monitor the operation status of DG units, to automatically adjust relay settings, and to make other necessary changes when the microgrid has any dynamic changes. Based on the concept of the CMCS, a SA fault current estimation algorithm is developed with the support of communication system. The CMCS will update online the operation status of RBDGs and IBDGs and properly adjust tripping current thresholds of the relays according to the results of the SA microgrid fault analysis proposed.

At the grid-connected operation mode of the microgrid, the total fault current seen by a relay r can be calculated as in (1):

$$I_{fault\_relay} = I_{fault\_grid} + \sum_{i=1}^{n} (k_i \times I_{fault\_DGi})^{Operation\_status\_DG}$$

where $I_{fault\_relay}$ is the total fault current seen by the relay r; $I_{fault\_grid}$ is the grid fault current contribution to the relay r; n is the total number of IBDGs and RBDGs penetrated into the microgrid; $k_i$ is a fault current coefficient for the relay r caused by the $i^{th}$ distributed generator (DG); in other words, $k_i$ is a fault current distribution factor of the DG under the grid-connected operation; and $Operation\_status\_DG$ shows connection/disconnection of the $i^{th}$ DG to the microgrid (i.e., $Operation\_status\_DG$ is equal to 1 in term of the $i^{th}$ DG connected to the microgrid; and otherwise $Operation\_status\_DG$ is equal to 0 in case of the $i^{th}$ DG disconnected to the microgrid).

A. Calculating the Grid Fault Current Component $I_{fault\_grid}$

It is assumed that faults are inside the microgrid. Calculation of the grid fault current $I_{fault\_grid}$ is based on Thevenin equivalent as the following:

$$V_{bus}(F) = V_{bus}(0) - Z_{bus}I_{bus}(F)$$

where $V_{bus}(F)$ denotes phase voltages of the bus during the fault; $V_{bus}(0)$ is the pre-fault phase voltage; $I_{bus}(F)$ is an array of fault currents flowing out of phases at the bus/node during the fault; and $Z_{bus}$ is a Thevenin impedance matrix.

When $Z_{bus}$ and $V_{bus}(0)$ are available, the grid fault current $I_{fault\_grid}$ is calculated as in (3),

$$I_{fault\_grid} = \frac{V_{bus}(0) - V_{bus}(F)}{Z_{bus} + Z_f}$$

where $Z_f$ is the fault impedance.

For unbalanced faults, a positive-, negative-, and zero-sequence Thevenin impedance matrix $Z_{bus}^{012}$ needs to be calculated (subscripts 0, 1, 2 are denoted as zero-, positive-, and negative-sequence components, respectively). Equation (2) can be re-written as in (4),

$$V_{bus}^{012}(F) = V_{bus}^{012}(0) - Z_{bus}^{012}I_{bus}^{012}(F)$$

When calculating the grid fault current contribution to different faulted sections inside the AC microgrid (e.g., faulted source/load branches), Eq. (3) can be rewritten as follows:

$$I_{fault\_grid} = \frac{V_{th}}{Z_{th}}$$
where $V_{th}$ is the Thevenin equivalent voltage of the utility grid [27]; $Z_{th}$ is the Thevenin impedance from the utility grid to a faulted location. The value of $Z_{th}$ changes depending on various faulted locations/types. It is worth noting that the system impedance at the PCC (point of common coupling) of the microgrid and microgrid network parameters are pre-known. Based on which, the grid fault current $I_{\text{fault,grid}}$ can be evaluated as the basis for tuning pick-up currents of adaptive OC/DOC relays inside the AC microgrid where $I_{\text{fault,grid}}$ can be much higher than the total fault current of DG units, $\sum_{i=1}^{n} I_{\text{fault,}DG_i}$, as assumed at the grid-connected operation mode of the microgrid. To further account for fault current contribution of DG units inside the microgrid, fault current distribution factor of DG units to each MG protective relay must be evaluated, as presented in the following part.

B. Calculating Fault Current Coefficients of DG Units to Each Relay

The close-in fault sequence current at the terminal of the $i^{th}$ DG, $I_{\text{fault,}DG_i}$, can be easily calculated according to pre-specified parameters of DG units (e.g., terminal voltages or positive-/negative-/zero-sequence impedances). To be simplified for fault calculation in small-scale low-voltage AC microgrids, the minimum close-in fault current produced by a rotating-based DG is about 5.0p.u; and the maximum close-in fault current of RBDGs is about 10p.u [28,29]. On the other hand, the maximum positive-sequence fault current of inverter-based DGs in the microgrid should be limited to 2.0p.u [4]. While RBDGs generate positive-/negative-/zero-sequence components to correspond with symmetrical and asymmetrical faults [30-32], IBDGs (i.e., VSC-coupled distributed energy resources) can be controlled to mitigate the negative-sequence current and only inject the positive-sequence current into the MG [30]. In addition, IBDGs can eliminate the zero-sequence fault current by using three-leg, three-wire interface-VSCs, or $Y/\Delta$ isolation transformers (with the $\Delta$ connection at the microgrid side) in case of four-leg, three-wire VSCs used. For some applications, IBDGs should inject a pre-determined negative-sequence current into the inverter-dominated microgrid, for example, for islanding detection [31] or microgrid protection [1,2]. Therefore, positive-, negative-, and zero-sequence models of IBDGs should be comprehensively considered for developing a SA fault current estimation approach for grid-connected LVAC microgrids.

![Figure 1. Positive-/negative-/zero-sequence models of the IBDG.](image)

Positive-/negative-/zero-sequence models of an IBDG are shown in Fig. 1(a), (b), and (c), respectively. The positive-sequence fault current, $I_{f,IBDG}^1$, is mostly limited to 2.0p.u. The negative-sequence fault current, $I_{f,IBDG}^2$, is reduced to a pre-specified value less than 5% [31]. The zero-sequence fault current contribution, $I_{f,IBDG}^0$, depends on different configurations of the IBDG (e.g., three-wire VSC-interfaced DGs, four-wire VSC-interfaced DGs). The $Y^{1,2,0}_{IBDG}$ parameters are sequence admittances of the IBDG.

A fault current coefficient $k_{ri}$ is used to express fault current contribution of the $i^{th}$ DG to the $r^{th}$ relay in the microgrid, which is calculated as in (6). For convenience of the presentation, $k_{ri}$ shall be first defined on the basis of a three-phase ($3\phi$) fault, so the following is presented only considering positive sequence components.

$$k_{ri} = \frac{I_{\text{fault,}DG_i,\text{relay}}}{I_{\text{fault,}DG_i}}$$

where $I_{\text{fault,}DG_i,\text{relay}}$ is the fault current contributed by the $i^{th}$ DG to the $r^{th}$ relay; this fault current varies depending on the Thevenin impedance value between the $i^{th}$ DG location and the $r^{th}$ relay location. For example, referring to Fig. 2, when an impedance of the $i^{th}$ DG, $Z_{DG_i}$, and the grid system impedance, $Z_{sys}$, are known, the fault current coefficient $k_{ri}$ is determined as in (7).

$$k_{ri} = \frac{I_{\text{fault,}DG_i,\text{relay}}}{I_{\text{fault,}DG_i}} = \frac{Z_{sys}}{Z_{DG_i} + Z_{sys}} I_{\text{fault,relay}}$$

where the current $I_{\text{fault,}DG_i,\text{relay}}$ can be viewed as the partial fault current of the total current $I_{\text{fault,relay}}$ seen by the relay $r$, as indicated in Fig. 2. The other fault current component of $I_{\text{fault,relay}}$ is the one provided from the utility grid. The fault current coefficient $k_{ri}$ can then be called ‘a current distribution factor’ of the close-in fault current $I_{\text{fault,}DG_i}$ of the $i^{th}$ DG to the $r^{th}$ relay. Consequently, one can evaluate the fault current coefficient of a specific DG unit to any protective relay inside the microgrid.

![Figure 2. Fault current contribution of the $i^{th}$ DG to the $r^{th}$ relay](image)

It is realised that the value of $k_{ri}$ is between 0 and 1. When $k_{ri}$ is approximate to 1, the location of the $i^{th}$ DG is close to the location of the $r^{th}$ relay or the $i^{th}$ DG and the $r^{th}$ relay can be all placed at the same source branch in a LVAC microgrid configuration. When $k_{ri}$ is much less than 1, the $i^{th}$ DG location is far from the $r^{th}$ relay or the fault current contribution of the $i^{th}$ DG to the relay is small. Moreover, it is worth considering that fault currents of IBDGs do not vary with distance (i.e., IBDGs become current sources during the fault), so fault current coefficients are not applicable to the...
IBDGs. In other words, a fault current coefficient of the IB DG is a unit value.

In general, a “K” fault current coefficient matrix is calculated to depict fault current contributions of a lot of DGs to many relays as indicated in (8). There are the ‘n’ number of DG units and the ‘m’ number of relays in the microgrid.

\[
K = \begin{bmatrix}
    k_{i1} & \cdots & k_{in} \\
    \vdots & \ddots & \vdots \\
    k_{m1} & \cdots & k_{mn}
\end{bmatrix}
\tag{8}
\]

In the above presentation, it has been assumed for the 3ϕ fault. The same procedure can be applied to unbalanced faults.

C. Calculating the Total Fault Current Seen by Each Relay

The close-in-fault currents of the ‘n’ number of DGs can be represented by a fault current matrix \( I_{\text{fault-DG}} \) with a dimension \([1, n]\), as in (9).

\[
I_{\text{fault-DG}} = \begin{bmatrix}
    I_{\text{fault-DG1}} \\
    \vdots \\
    I_{\text{fault-DGn}}
\end{bmatrix}
\tag{9}
\]

From equations (8) and (9), the fault currents produced by the “n” number of DGs seen by the “m” number of relays are:

\[
I_{\text{faultDG relay1}} = \sum_{l=1}^{m} k_{l1} I_{\text{fault-DG1}} + \sum_{l=1}^{m} k_{li} I_{\text{fault-DGi}} + \sum_{l=1}^{m} k_{ln} I_{\text{fault-DGn}}
\]

As a result, equation (1) can be re-written as the following:

\[
I_{\text{fault relay1}} = I_{\text{fault grid relay1}} \oplus I_{\text{fault DG relay1}}
\]

\[
I_{\text{fault relay2}} = I_{\text{fault grid relay2}} + I_{\text{fault DG relay2}}
\]

\[
I_{\text{fault relaym}} = I_{\text{fault grid relaym}} + I_{\text{fault DG relaym}}
\]

Due to the support of communication channels, fault current contributions of IBDGs, RBDGs, and the utility grid can be continuously observed in a grid-connected LVC microgrid. Moreover, the ‘K’ fault current coefficient matrix, and the \( I_{\text{fault-DG}} \) close-in-fault current matrix of DG units can be constantly monitored and updated. Consequently, total fault current values seen by adaptive OC/DOC relays can be quickly estimated to correspond with the plug-and-play and peer-to-peer characteristics of the AC MG. Fault tripping current thresholds of the relays can be properly changed. In case of a communication system failure, the latest total fault current values will be kept at the relays until communication links are restored. At this situation, a microgrid back-up protection system should be activated after a certain time-due to timely detect and clear the faults that occur at the time coincidental to the communication failure time.

D. Evaluation of the Simplified and Automated Fault Current Calculation Approach

At the grid-connected operation mode of the microgrid, the direction of fault currents can be determined. In particular, downstream fault currents will flow from the utility grid side into the microgrid side or from the microgrid into DG-source/load branches or energy storage branches. Upstream fault currents will flow from the microgrid back to the utility grid side or from DG-source/energy-storage branches into the microgrid. Downstream fault currents at DG-source/load branches or energy storage branches can be quickly calculated by the SA fault current estimation algorithm as aforementioned.

On the other hand, to calculate fault currents seen by the relays placed at trunk lines or common buses in the microgrid, it is necessary to determine which relays will observe upstream or downstream fault currents. According to fault current coefficients of the utility grid and DG units, downstream and upstream fault currents seen by the relays on the trunk lines and the common buses will be calculated by the SA fault current estimation algorithm. By referring to Fig.
3, with a single-line diagram of a radial AC-microgrid configuration, a relay-i observes downstream fault currents flowing from the utility grid and a DG-i, whereas a relay-j observes an upstream fault current flowing from a DG-j. A downstream fault current coefficient \( k_i \) of the DG-i to the relay-i is zero. Similarly, an upstream fault current coefficient \( k_j \) of the DG-j to the relay-j is zero.

### III. APPLICATION OF THE SA FAULT ANALYSIS APPROACH TO A LVAC MICROGRID PROTECTION SYSTEM

#### A. Operating Principle of a LVAC-MG Protection System

At the grid-connected operation mode, adaptive DOC/OC protection modules in an AC-microgrid digital relay are used to detect and clear faults. A simplified and automated fault current estimation approach is proposed to accurately determine downstream and upstream fault currents in the microgrid. Therefore, fault tripping current thresholds of the adaptive DOC/OC protection modules can be continuously and properly adjusted to correspond with different fault locations/types as well as configurations of the microgrid. To be convenient for the presentation, it is necessary to distinguish between downstream/upstream fault currents and downstream/upstream relays in the microgrid. For instance, when a fault occurs inside the microgrid, an upstream relay of the fault is to observe the downstream fault current contributed by the utility grid towards the MG side, whereas a downstream relay of the fault is to observe the upstream fault current contributed by DG-source/energy-storage branches towards the grid side.

Fig. 5 shows the operating principle of a LVAC microgrid fault protection system under the grid-connected operation mode. By referring to note (2) in Fig. 5, when a fault occurs at a load branch or a DG-source/energy-storage branch, the total downstream fault current can be sufficiently high to activate adaptive OC protection modules within less than two cycles. Considering note (1) in Fig. 5, when a fault occurs on a trunk line or a common bus, the downstream grid fault current is very high so that DOC protection modules upstream of the fault will be activated to quickly clear the fault. However, upstream fault currents may not be sufficiently large to actuate the DOC protection modules downstream of the fault, which depend on different penetration levels of IBDGs and RBDGs into the microgrid. To solve this problem, if an upstream relay of the fault is activated, tripping signal and information about direction of phase currents will be sent to adjacent downstream relays via a neighbour communication system. Based on interconnection links, only if the upstream relay has already been tripped, its adjacent downstream relays will interrupt right after. Referring to note (3) and note (5) in Fig. 5, existing fault protection modules based on zero-/negative-sequence current/voltage components are mostly suitable to detect high-impedance faults [1,2]. In order to locate the high-impedance fault on the trunk line/common bus, one can conclude that if either the upstream relay of the fault or its adjacent downstream relays figure out the directional change in phase currents, the high-impedance faulted location is among these relays, as mentioned in note (6) of Fig. 5.

#### B. Structure of a Multi-grounded 380V AC MG Test-Bed

A 380V AC microgrid test-bed includes a 65kW micro-turbine generation system connected to a main line through a 100kVA \( Y/Y_1 \) isolation transformer. A 31.5kW High-
Concentrated Photovoltaic (HCPV) generation system is additionally used. A battery power coordinating system (PCS) has a power density of 100 kWh, which is connected to a trunk line through a 150 kVA \( Y \) transformer. This AC microgrid test-bed consists of 36 kW loads. In addition, specifications of each electrical component of the studied microgrid can be seen in Fig. 6.

Three faulted locations are surveyed at the microgrid, including: i) faults at an AC trunk line (F1), ii) faults at a MT source branch (F2), and iii) faults at a load branch (F3). As shown in Fig. 6, current and voltage measurement points are coincident to locations of microgrid digital relays (MDR). There are MDR1, MDR3, MDR4, MDR5, MDR6, MDR7 and a static switch (SS). Three-phase to ground faults (TPGF), single-phase to ground faults (SPGF), phase-to-phase faults (PPF), and double-phase to ground faults (DPGF) are assumed to occur in the multi-grounded 380V AC microgrid. Table I summarises fault simulation situations of the 380V AC microgrid during the grid-connected operation mode. As mentioned in Fig. 5 at Section 3.1, adaptive DOC/OC protection modules embedded in a microgrid digital relay are proposed to primarily protect load branches, DG-source/energy-storage branches, or trunk lines/common buses of the LVAC microgrid under the grid-connected mode.

**TABLE I. MICROGRID FAULT SITUATIONS UNDER THE GRID-CONNECTED OPERATION MODE**

<table>
<thead>
<tr>
<th>Fault locations</th>
<th>Fault types</th>
<th>Protective relays of the microgrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downstream relays</td>
<td>Upstream relays</td>
<td></td>
</tr>
<tr>
<td>Fault at a trunk line (F1)</td>
<td>TPGF</td>
<td>MDR7</td>
</tr>
<tr>
<td>Fault at a micro-turbine source branch (F2)</td>
<td>TPGF</td>
<td>None</td>
</tr>
<tr>
<td>Faults at a load branch (F3)</td>
<td>TPGF</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>SPGF</td>
<td>MDR3</td>
</tr>
<tr>
<td></td>
<td>PPF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DPGF</td>
<td></td>
</tr>
</tbody>
</table>

At the grid-connected operation mode of a LV AC microgrid

1. Protect trunk lines/common buses
2. Protect DG-source/energy-storage branches and load branches
3. Use adaptive directional overcurrent (DOC) protection modules
4. Is the tripping time of DOC/OC protection modules less than two cycles?
   - YES
   - NO
5. Fault is detected and located by DOC/OC protection modules
6. Is there any directional change in phase currents?
   - YES
   - NO
7. Fault is detected and located by protection modules not based on high fault phase currents
8. Protection modules not based on high fault phase currents are activated (e.g., 27, 46, 47, 3I0, 3V0)
9. Is there any difference in the direction of phase currents among adjacent relays?
   - YES
   - NO
10. Fault is detected and located by protection modules not based on high fault phase currents

**Figure 5. Operating principle of a LVAC-MG fault protection system under the grid-connected operation mode**

Note: This AC-MG fault protection system is mainly focused on fault detection and location in the LVAC microgrid under the grid-connected operation mode.
### Table II. Tripping Settings of Fault Protection Modules in the AC Microgrid Digital Relay Corresponding With Different Fault Locations (F1–F3)

<table>
<thead>
<tr>
<th>Fault locations</th>
<th>Protective relays</th>
<th>Estimated fault currents (*)</th>
<th>Overcurrent protection modules</th>
<th>Other protection modules</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( I_{\text{max}} ) (kA)</td>
<td>( I_{\text{fmax}} ) (kA)</td>
<td>( I_{\text{pick-up}} ) (kA)</td>
</tr>
<tr>
<td>F1</td>
<td>MDR6</td>
<td>0.220 (9.52)</td>
<td>0.440 (11.10)</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>MDR7</td>
<td>0.220 (3.29)</td>
<td>0.440 (3.90)</td>
<td>0.70</td>
</tr>
<tr>
<td>F2</td>
<td>MDR1</td>
<td>0.125 (3.42)</td>
<td>0.250 (4.14)</td>
<td>0.50</td>
</tr>
<tr>
<td>F3</td>
<td>MDR3</td>
<td>0.974 (11.54)</td>
<td></td>
<td>1.20</td>
</tr>
</tbody>
</table>

(*) The current values in brackets are the downstream fault current values observed by the digital relays. The current values outside brackets are the upstream fault current values estimated in the multi-grounded 380V AC MG.

### C. Relay Settings in a Microgrid Fault Protection System

Based on a simplified and automated fault current estimation approach developed for grid-connected LVAC microgrids, minimum and maximum fault currents (\( I_{\text{min}} \) and \( I_{\text{max}} \), respectively) seen by each relay can be calculated to correspond with different faulted locations (F1–F3) in the multi-grounded 380V AC microgrid. Hereby, pick-up currents (\( I_{\text{pick-up}} \)) of adaptive DOC/OC protection modules can be properly adjusted. An inverse current-time tripping characteristic of DOC/OC protection modules (according to the standard IEC60255) is used, referring to equation (13).

\[
t = TD \left( \frac{A}{I_{\text{fault}}} \right)^p + B
\]

where time-dial setting (\( TD \)) is 0.05, \( A = 8.9341, p = 2.0938, B = 0.17966; I_{\text{fault}} \) is the total fault current seen by the DOC/OC protection module.

On the other hand, in order to set tripping thresholds of protection modules based on negative/zero sequence
current/voltage components, the tripping thresholds should be at least three times load unbalance values of 20% [1,2]. Table II shows tripping settings of critical fault protection modules (e.g., 50/51, 67, 46, 47, 3I_o and 3V_o) in each AC-microgrid digital relay to protect the 380V AC microgrid against faults at F1–F3. It is noted that the protection modules 46, 47, 3I_o or 3V_o are the back-up protection solution of DOC/OC protection modules (e.g. 50/51/67) during the grid-connected microgrid operation. A time-grading strategy is used to coordinate between main protection modules and back-up protection modules in the AC-microgrid digital relay. In particular, a coordination time interval between the protection modules in the AC-microgrid digital relay is set at two fundamental cycles.

IV. VALIDATION OF THE SA FAULT CURRENT ESTIMATION APPROACH PROPOSED FOR LV AC MICROGRIDS THROUGH FAULT SIMULATION RESULTS

A. Fault Protection of a Load Branch (F3)

During the grid-connected operation mode of the AC microgrid, an overcurrent protection module of a microgrid digital relay is used as primary protection of a load branch. The total downstream fault current flowing from an 11.4kV distribution grid and DG-source branches to a faulted load branch-F3 is very high so that the OC protection module can quickly detect and clear faults within two cycles (about 33.33ms). Figures 7–10 show the tripping time of the OC protection module with regard to various fault types at F3, specifically, a single-phase to ground fault, a phase-to-phase fault, a three-phase to ground fault, and a double-phase to ground fault, respectively. Observing fault current and voltage waveforms in Figs. 7–10, main evaluations are given as follows:

- The tripping time of the OC protection module in MDR3 is within two cycles to detect and clear the SPGF, PPF, TPF and DPGF at F3. By applying the SA fault current estimation approach, the total downstream fault current seen by the MDR3 can be accurately determined. Therefore, the pick-up current as well as time-dial setting of the OC protection module can be effectively adjusted to ensure a ‘fast’ fault clearing time of the MDR3 at the load branch.
- In Figs. 7–10, BRKMDR3_m represents a tripping signal of the OC protection module in MDR3. BRKMDR3_b represents a tripping signal of back-up protection modules in MDR3 (e.g., fault protection modules based on sequence current/voltage components). If the OC protection module does not trip within two cycles, the back-up protection modules will be activated to timely detect and clear the faults at F3.

![Figure 7](image_url)

**Figure 7.** SPGF currents and voltages at F3 and the tripping time of the OC protection module in the MDR3

![Figure 8](image_url)

**Figure 8.** DPGF currents and voltages at F3 and the tripping time of the OC protection module in the MDR3
B. Fault Protection of a Trunk Line (F1)

MDR6 will observe downstream fault currents flowing from an 11.4kV distribution grid and a 65kW micro-turbine source branch into a faulted location-F1. The other AC-microgrid digital relay, MDR7, will observe upstream fault currents produced by a PV source branch and a battery power conditioning system (PCS). The total downstream fault current seen by MDR6 is very high so that MDR6 can trip at less than two cycles. Meanwhile, MDR6 can detect the directional change of current on the faulted phase, by referring to Fig. 11. As shown in Fig. 11, the tripping time of the DOC protection module in MDR6 is about 28ms for a three-phase to ground fault (TPGF) at F1. On the other hand, the total upstream fault current seen by MDR7 is small because of fault current limitation from IBDGs (i.e., a PV source branch and a battery PCS branch in the 380V AC microgrid). Therefore, adaptive DOC/OC protection modules in MDR7 cannot be activated. However, due to a neighbour communication system between MDR6 and MDR6, the tripping signal and the information about the direction of phase currents of MDR6 are transmitted to MDR7. It is noted that MDR7 cannot detect the directional change of phase currents while MDR6 can do that. As a result, MDR7 will be timely activated to interrupt the upstream fault currents flowing into the faulted location-F1 on the trunk line, by referring to Fig. 12. Moreover, the fault detection time of back-up protection modules in MDR7 is about 35ms. The back-up protection modules are only activated after a two-cycle coordination time interval.

A downstream fault current from the grid to any faulted location on the trunk line is much higher than downstream fault currents from DG-source branches. When some DG-source branches in the LVAC microgrid do not operate, the total downstream fault current is still sufficient to actuate the DOC protection modules. A neighbour communication system between MDR6 and MDR7 plays an important role to locate faults on the trunk line of the microgrid. If the neighbour communication system fails, back-up protection modules in MDR7 can still be activated to clear the faults at F1. Table III shows a comparison on total downstream/upstream fault currents seen by MDR6 and MDR7 which are calculated by the simplified simulation method. An error in fault current values between the automated fault current estimation approach and a fault simulation method. An error in fault current values between two above methods is less than 10%.

C. Fault protection of a DG-source branch (F2)

The total downstream fault current flowing into a faulted location-F2 is sufficiently high to quickly activate a microgrid digital relay-MDR1. Referring to Fig. 13, fault clearing time of an OC protection module in MDR1 is about 18ms. Besides that, MDR1 can detect the directional change
of phase currents at the faulted MT source branch. As a result, the simplified and automated fault current estimation approach for the LVAC microgrid is effective to be applied for properly adjusting pick-up currents of DOC/OC protection modules in microgrid digital relays under the grid-connected operation mode. Therefore, ‘fast’ fault clearing characteristic of a LVAC microgrid protection system can be achieved and has been successfully demonstrated through a three-phase to ground fault event at the micro-turbine source branch of a 380V AC microgrid test-bed.

<table>
<thead>
<tr>
<th>Fault at F1</th>
<th>A SA fault current estimation approach</th>
<th>A fault simulation method based on PSCAD software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min: 9.52kA</td>
<td>Max: 11.10kA</td>
<td>9.21kA</td>
</tr>
</tbody>
</table>

V. CONCLUSION

This paper has presented a simplified and automated fault current estimation approach for small-scale grid-connected AC microgrids with presence of both rotating based DGs and inverter-based DGs. The proposed SA fault current estimation approach is effective to quickly and accurately calculate fault current contributions from rotating-based DGs, inverter-based DGs, and the utility grid due to the support of communication system. Under the grid-connected operation mode of LVAC microgrids, fault tripping current thresholds of adaptive OC/DOC relays can be properly self-adjusted according to fault current distribution coefficients of all DG units and the utility grid over each protective relay as well as fault current values determined by the simplified and automated fault analysis method.

In short, the main contribution of this study is to develop a novel SA fault analysis method which can be applicable to different configurations of low-voltage AC microgrids and fault behaviours of IBDGs and easily adaptable to the dynamic changes in the microgrid by using a central microgrid control system (CMCS) communicating with all DG units and protective relays. Application of the SA fault analysis approach to a multi-grounded 380V AC-microgrid fault protection system during the grid-connected operation mode has been investigated. This microgrid protection scheme uses adaptive OC/DOC relays as the primary fault protection. Fault simulation results have been discussed to validate the proposed SA fault current calculation algorithm for grid-connected AC microgrids. In future, the simplified and automated fault current estimation approach for LVAC microgrids can be expanded to large-scale AC microgrids operating at distribution voltage levels. More attention could be paid to the communication protocol to execute data communication between the CMCS and the DG units and the protective relays in the microgrid.

![Fault inheritance time](image1)

**Figure 11.** Downstream fault currents are observed at MDR6 and its tripping signal with regard to a TPGF at F1

---

TABLE III. TOTAL DOWNSTREAM/UPSTREAM FAULT CURRENTS ARE SEEN BY MDR6 AND MDR7

<table>
<thead>
<tr>
<th>Fault</th>
<th>Downstream fault current seen by MDR6</th>
<th>Upstream fault current seen by MDR7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-phase to ground fault</td>
<td>Min: 0.220kA Max: 0.440kA</td>
<td>0.297kA</td>
</tr>
</tbody>
</table>

V. CONCLUSION

This paper has presented a simplified and automated fault current estimation approach for small-scale grid-connected AC microgrids with presence of both rotating based DGs and inverter-based DGs. The proposed SA fault current estimation approach is effective to quickly and accurately calculate fault current contributions from rotating-based DGs, inverter-based DGs, and the utility grid due to the support of communication system. Under the grid-connected operation mode of LVAC microgrids, fault tripping current thresholds of adaptive OC/DOC relays can be properly self-adjusted according to fault current distribution coefficients of all DG units and the utility grid over each protective relay as well as fault current values determined by the simplified and automated fault analysis method.

In short, the main contribution of this study is to develop a novel SA fault analysis method which can be applicable to different configurations of low-voltage AC microgrids and fault behaviours of IBDGs and easily adaptable to the dynamic changes in the microgrid by using a central microgrid control system (CMCS) communicating with all DG units and protective relays. Application of the SA fault analysis approach to a multi-grounded 380V AC-microgrid fault protection system during the grid-connected operation mode has been investigated. This microgrid protection scheme uses adaptive OC/DOC relays as the primary fault protection. Fault simulation results have been discussed to validate the proposed SA fault current calculation algorithm for grid-connected AC microgrids. In future, the simplified and automated fault current estimation approach for LVAC microgrids can be expanded to large-scale AC microgrids operating at distribution voltage levels. More attention could be paid to the communication protocol to execute data communication between the CMCS and the DG units and the protective relays in the microgrid.

![Fault inheritance time](image2)

**Figure 11.** Downstream fault currents are observed at MDR6 and its tripping signal with regard to a TPGF at F1
Upstream fault currents are observed at MDR7 and its tripping signal (BRKMDR7) with regard to a three-phase to ground fault at the trunk line-F1. The fault detection time of MDR7 is about 35ms. High total harmonic distortion percentages of phase currents ($THDi_a$, $THDi_b$, & $THDi_c$) and voltages ($THDV_a$, $THDV_b$, & $THDV_c$) are seen at MDR7. The fault inception time is at the 43rd second. The direction of phase currents does not change during the three-phase to ground fault.

Fault detection time of an OC protection module in MDR1 is about 18ms. Fault clearing time of F2 is 18ms.

Downstream fault currents ($I_a$, $I_b$, and $I_c$) and voltages ($V_a$, $V_b$, and $V_c$) are observed at MDR1 and its tripping signal (BRKMDR1) for a three-phase to ground fault at the MT-source branch-F2. The fault inception time is at the 45th second. The direction of phase currents changes during the three-phase to ground fault at F2.
ACKNOWLEDGEMENTS

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REFERENCES

Consideration for Use of Traditional Structure to Designing for Flexible Modern Furniture through Lu Ban Lock

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Abstract—It is inspired to use tenon joint structure for furniture design, in which pieces of furniture can be assembled with or combined action flexibly to achieve offer flexibility furniture assembly and a sense of to have fun, as well as to achieve space-saving and mobility functions easy to carry during transportation. Use the 3D printer make models to help study the advantages and disadvantages of the traditional combination on toys - puzzle games in order to generate applicable concepts in apply the using of methodology to for furniture design.

Keywords—Lu Ban Lock; Tenon and mortise structure; Modern Furniture; 3D printer

I. INTRODUCTION

Chinese furniture history in the development of the first peak, at LiangZhou period. The old style is actually the continuation of life is always retro creation in constant. Later the tall feet sitting furniture's era changes caused by natural revolutionary, but the shape and the basic elements of the production process is still a source of wisdom can be found in the classical memory.

Ming Dynasty furniture style is very simple and clean, craft production, the functions of use have reached unprecedented heights. This period furniture, variety, style is extremely rich. Furniture concept has been formed. The method is usually symmetrical layout, such as a table and two chairs or a group of four stools and so on, a lot of use in the production of hard texture, high intensity resistance precious wood. Furniture made tenon structure is very sophisticated, very concise outline section and small components, moldings meticulous workmanship, technology has reached a very high level, forming a Ming Dynasty furniture, simple and elegant, beautiful and dignified, rich flavor, hardness and softness unique style.

Tenon joint structure is a traditional Chinese architecture and furniture construction.

This paper intends to provide a way to use the stability tenon structure, a combination of furniture into a unitary structure. The purpose is to easy transport, increased variability use of furniture and It gives us pleasure. In the next section, at a certain system, basic definitions and terminology of this topic are given. Then an overview of existing technologies and also recent advances in the field is provided. After that is the research demonstrate at this stage. This is followed up by a description on the different architectures of furniture design. The final sections pertain to description on some of the applications of furniture design and future directions in the field.

II. ABOUT SOME OF THE TERMINOLOGY

Perhaps many people played Lu Ban lock, maybe a lot of people have not seen it. Let's look at a few concepts we study.

A. Lu Ban Lock

Lu Ban (507–440 BC) was an ancient Chinese carpenter, engineer, and inventor. He was a contemporary of Mozi, and he is the patron saint of Chinese builders and contractors.

The Lu Ban Lock is an educational toy named after by Lu Ban.

Legend has it that during the Spring and Autumn Period, the master craftsman Lu Ban wanted to test if his son was clever. He made a detachable toy with six wooden slips and asked his son to tear it apart. After a whole night work, his son succeeded in doing it. The toy was named "Lu Ban Lock" by later generations.

This is just a legend. Actually, Lu Ban lock, also known as Kongming lock, Never-Boring Sticks, the Six Interlocking Blocks, No Way Out and Trouble Blocks etc. It was derived from the tenon structure initiated in ancient Chinese architecture.

The toy is based on a structure composed of mortise and tenon joints structure. Each piece of the lock is interconnected without fixtures, and players have to unlock the gadget and then put the pieces back together. It was widely popular among the folks. The concave and convex parts inside the three-dimensional interpolation toy mesh perfectly. It come in different shapes and sizes, with different internal structures. But they are usually easy to take apart and difficult to reassemble.
B. Tenon and mortise structure

Fig. 1. Lu Ban lock

Tenon joint structure is a way of joining the two components connected wood furniture used. There is also applicable to other bamboo, stone artifacts in. Chinese ancient buildings and furniture, mainly wood as the main material, wood frame structure for major structural way junction between the various components in order to coincide tenon form flexible framework. Tenon is a bump on the connection of two wooden components used in combination. Protruding part called tenon; recessed portion called mortise, the hole of one of the tenon mortise into another, the tenon and mortise bite, role play connection. Can effectively limit the twist pieces of wood in all directions.

C. Modern Furniture

Modern furniture is the physiological condition of the body to adapt to the modern, lifestyle, living environment to the needs of the production unit facility. With the development of the times, the modern cultural cultivation and aesthetic taste and the ancients also very different. Modern furniture stand improvement, traditional furniture only innovation can adapt to modern needs new life and aesthetic requirements.

D. 3D printer

3D printing materials are usually printers using digital technology to achieve. Often in the mold manufacturing, industrial design and other fields are used to make the model, gradually for direct manufacturing of some products, has made use of this technology to print parts. The technology in the jewelry, footwear, industrial design, architecture, engineering and construction (AEC), automotive, aerospace, dental and medical industries, education, geographic information systems, civil engineering, firearms, and other fields have applied.

III. Research Tenon Structure

This combination can effectively limit the twist in every direction between pieces of wood. And nail connection can not do that. For example, nails will be two wood T font combination, vertical column and transverse column is easy to be distorted and change the angle, and combining with tenon and mortise, it can not be distorted. Secondly, the metal is easy to rust or oxidation, and the genuine mahogany furniture, can use hundreds or thousands of years. Many of the Ming Dynasty style furniture dating back hundreds of years, although the show vicissitudes of life, but the hard wood. If this combination of furniture nails, probably wooden intact, but because the connection of metal corrosion, fatigue, aging, and make the furniture apart.

A lot of mahogany furniture and transport, to the destination assembling together, very convenient. If the connection furniture nails, although it can be made into separate parts, but like chair wooden pieces of furniture, can not do that.

Nails connected furniture, do the disassembly and replacement is not like the mortise and tenon structure furniture easy. While the use of mortise tenon joint mahogany furniture, can greatly enhance the inherent quality of annatto furniture, this is an important reason for the production of traditional mahogany furniture has the added value of collection.

From ancient times, the furniture plays a very big role in our lives, the following specific research in several areas.

A. History and present

The Lu Ban Lock uses the principles of the Chinese traditional tenon joint structure in it’s for design. It is one of the country’s traditional toys with a long history. In the old days, it was once the ancient Chinese carpenters were required to produce this piece to find entry a compulsory production work. The Lu Ban Lock tenon structure forms as traditional educational toys that are a heritage pieces in China. These toys have a compact structure and serve as the function of decoration when not used for and play fun. This type of toy is a favorite overall sense widely spread among the people is it is a favorite Chinese.

The tenon and mortise structure, which dated dates back to nearly 7,000 years ago, plays an important role in the construction and home design for its unique. We excavated the tenon and mortise structure’s woods from Yuyao County,
Zhejiang Province, China in 1973. The age of the culture was ca.5000-7000 years ago. As one of the major Neolithic cultures in the Yangtze River region.

![Image](Fig. 3. Tenon and mortise structure's woods in Yuyao County)

Premier Li Keqiang, China's head of government. He gave German Chancellor Angela Merkel a Lu Ban Lock, a traditional Chinese puzzle game, when that Lu Ban Lock to German Chancellor Angela Merkel as they attended a China-Germany economic and technological cooperation forum in Berlin, Germany, last October. 10, 2014. Li said he hopes cooperation between China and Germany can keep evolving and improving. The two countries can cooperate to solve global challenges together just like unlocking the Luban Lock, Li said.

![Image](Fig. 4. Li Keqiang and Angela Merkel)

T. Tanaka studied tenon structure. He get the research challenges about junction in 2008. He researched to development of a wooden puzzle containing wooden joints designed to teach elementary school students how to calculate volume. His paper explains the development of a wooden puzzle containing wooden joints designed to teach elementary school students how to calculate volume. An experiment was performed with the puzzle, which is a cube with wooden joints, targeting 1st-grade students. The shape of the puzzle is known to be difficult for children to work with. Next, we introduce the results of a test of volume calculation designed for children and describe the methods used to teach volume calculation in Japan. Finally, we compare the concepts of volume calculation and how to create a three-dimensional object in 3D-CAD to reveal that the ideas are almost identical.

**B. Characteristics of tenon and mortise**

Tenon and mortise structure has characteristics, such as the convergence and the friction of the body's own structure, reasonable structure, and the elimination of the various stress parts of the stress. The combination position of all these properties has ensured the longevity of can make thousand-year-old undestroyed buildings and furniture.

- The tenon joint structure is highly durable.

It elastic deformation and can offset some energy stress when a structure is subjected to force violence by their own elastic deformation, thereby in order to reducing the damage to the structure. The Mortise structure is continues to be still in use in Japanese architecture and furniture design heritage. Like China's Pagoda of Fogong Temple in Ying County, Shanxi province, China, is a wooden Chinese pagoda built in 1056, during the Khitan-led Liao Dynasty. It has survived several large earthquakes throughout the centuries.

![Image](Fig. 5. Pagoda of Fogong Temple)

Japanese architecture relies on the self-balance between the timber used in the building timber and flexibility of the tenon and mortise structure joints flexible node, to obtain the phenomenon of "wall collapsed but house is not destroyed", thereby ensuring and the preservation of life and property safety of the people in Japan, an earthquake-prone country.

- House wall collapsed house does not collapse.

Compared with modern architecture, ancient architecture in the traditional “tall” rare, even the most burly figure of the China's Palace of Supreme Harmony, even on the base, but also more than 30 meters, equivalent to only about the height of 10 storeys.

This is mainly because the ancient architecture of load-bearing timber, the timber itself is highly limited, if you want to build high palaces, you need to be a steadily pier wood together, the relative seismic worse, so the building height is limited. But wooden beams play the leading role, but it created a "House wall collapsed house does not collapse" the strange phenomenon.

Builders accordance with the size and shape of the house, on the basis of the location of the wall reserved for the
installation of stone capitals, as a future pillar of the "foundation." After that, in respect of the beam column. Because most of the buildings are ancient pattern with three bays, a large bay, the middle two beams, plus the front beam, rear beam total is four beams, intended to take on behalf of all sides, both ends of each beam of each pillar. The whole building has to rely on these four beams and eight supporting pillars.

Unlike modern load-bearing walls, the walls of ancient buildings mainly plays shelter, heat insulation and other functional roles. As long as beams does not fall, even if the wall collapsed, the main structure of the house will not collapse.

Also, because the walls of houses does not load weight, doors and windows are provided great flexibility. And this wood frame structure forms a unique element in the past palaces, temples, and other senior building only, namely under the eaves "mountainous" in brackets. The role of this component of both the load-supporting beams and decorative effect.

- **Tenon construction without nails.**

Chinese ancient buildings on the main wooden structures are used tenon structure, without nails, skilled, the structure is very complex. The tenon joint structure does not require the use of without a nails, a ropes, or even a drop of glue; it relies, just on its own convex and concave shapes, retreat, and rotation, and it can be securely snap together securely based on a set of methodical, each step methodically. This innovation Reflects China's dynamic concept for and still load coupling, and on a deeper level, such philosophies as retreating in order to advance, the pursuit of perfection, philosophy and inherent principle for each action of doing things.

![Fig. 6. Shenyang Imperial Palace](image)

In Shenyang Imperial Palace buildings, Manchu folk art can best embody the charm of the building, is a major political temple. Hall is not only a major political Shenyang Imperial Palace East of the main building, but also China's unique style palace temple account. Both with strong Manchu characteristics, but also the integration of the Han, Mongolian, Tibetan cultural connotation, and its construction techniques, thus becoming an example of a special hall of the palace, the national architectural treasures. This architectural pattern, only this palace building in China example. And that this magnificent, majestic towering basilica, from inside to outside is not even a nail.

C. **Asian and non-Asian different tenon furniture**

While we can find tenon structure around the world. But the different in using. Asian furniture tenon structure is complex and varied, but they are in the internal structure. Surface rounded and smooth. Like Asians are introverted, understated and steady. Tenon joint structure is exposed connections in non-Asian, like where personality, bold and straightforward.

![Fig. 7. Chair armrest](image)

![Fig. 8. CHAIR 23D](image)

The reason for this difference tenon structure design, there are aspects of materials, processes, technology, history, environment, people's character traits to decision.

However, due as producing to the tenon and mortise structure joint process is complexity and diversity varied, and its implementation requires time and effort, this structure is no longer popular founded in modern life in China. It is on the risk of being lost. Similarly, Due to the constraints of productivity conditions are among the reasons that such type of no binding was in studied together with furniture design has not been studied, now.
IV. MY DESIGN

Based on these gathered data research, I try to use modern three-dimensional carving techniques are used to reduce the difficulty in producing of the tenon and mortise structure produced, to improve accuracy, and to expand the scope of its application. By taking use of the natural environmental, aesthetic characteristics of wood are maximized in to designing a tenon and mortise structure removable combination modular pieces of furniture that feature a tenon and mortise structure; such furniture, which can be more would be adaptable to different spaces and different habits in human life.

This research will study about the structure of the Lu Ban Lock, including also study the advantages and disadvantages of the traditional combination on toys - puzzle games in order to generate applicable concepts in apply the using of methodology to for furniture design. Further, also in this study will consider about the user characteristics, such as ages, personality characteristics, living conditions, and living environments, to find determine out the suitable furniture designs for assembly and transport. In terms of material, this work I will try to determine a the different relationships between the physical and chemical properties of materials in the combinations of furniture pieces. Also find a suitable point of material combinations will be identified.

This study will also focus on changing the way people used to carry transport or move separate pieces of furniture dispersed. It will use furniture features that can be stylized separately and then it interspersed itself to be combined into one overall stable structure has a certain stability. This design will, in order to save space, allow repeated assembly and disassembly, and convenient transportation.

So the design is inspired by Lu Ban Lock has inspired furniture design, in which pieces of furniture can be assembled with or combined action flexibly to achieve offer flexibility furniture assembly and a sense of to have fun, as well as to achieve space-saving and mobility functions easy to carry during transportation.

In this research analysis, I have been designing models by using relevant computer software and then making create physical models, which will aid in the in order to easily understanding of for participants in design.
This research aims to remove the study of the Lu Ban Lock in its current existing form, including the structure, the formation, the art, the internal geometrically principles, and physical operational mechanism. Subsequently, and this work may to find a balance between the degree of structure in the form of difficulty in assembling the designed furniture and the Lu Ban Lock. With the research findings can be, it is expected to contribute to the design and assembly of a series of flexible and reassembly-enabled furniture, and thereby promoting to achieve convenience and artistic for furniture design and usage.

V. CONCLUSION

Through research and made the model, proved that we can by Lu Ban Lock's tenon joint structure design Furniture feasible. Flexibility to use a combination of various components of the body relative freedom to use different functions. When you need to transport or organize, assemble the various parts of the center can be as a whole, to save space.

VI. FUTURE PLAN

I hope to production of furniture is designed to be used to further study about its status in real life.

This is the result of my studies at this stage, in future research, I hope to carry out research and design with materials. In which I hope can be used of materials which combination self-performed in the furniture design. May be 4D printing technology for product technical analysis can do. I hope this furniture design to bring more convenient and comfortable life!

REFERENCES

Session 5: Sustainability and Policy

Learning Style Instruments and Impact of Content: A Qualitative Study
(Authors: Alzain Meftah Alzain, Gren Ireson, Steve Clark, Ali Jwaid)

A Multi-criteria Methodology to Select the Best Wave Energy Sites
(Authors: André Martinez, Zied Ben Mustapha, Rose Campbell, Tarik Bouragba)

Comparative by simulating the eventual waste generation of building indoor pavements construction
(Authors: Gómez-Soberón, J.M., Gómez-Soberón, M.C., Saldaña-Márquez, H., Gámez-García, D.C., Arredondo-Rea, S.P., Corral-Higuera, R.)
Learning Style Instruments and Impact of Content: A Qualitative Study

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Abstract—This qualitative study explores the nature and forms of information that can be used to construct a learning style instrument and to what extent the visual and active content can affect the preferences being measured. Six Masters students participated in this study, the preferred learning style of participants was measured twice, once by the VARK approach and once by the developed instrument which was enhanced by visual and active forms of information. The results of both approaches were compared and an interview with each participant has been conducted to further investigate the outcomes. The results of this study show that using a visual and active content for constructing the learning style instruments has a significant effect on the measured preferred learning style of students. This approach may lead to a more balanced assessment of learning style.

Keywords - learning; visual; active; content; adaptive

I. INTRODUCTION

Learning style instruments are built on the premise that there is no specific teaching approach or curriculum that fits all students [1-3] because they have both different preferences and abilities. Therefore, to enhance the outcomes of the education process, the differences amongst students need to be considered in our teaching. Numerous studies show that if the teaching environment is employed to match the students’ preferred learning style, learning will be better, easier and faster and a students’ performance will be increased [2-5].

As shown in Table 1, there are a number of well-known learning style models and instruments which could be used to detect the preferred learning style of students [1, 6, 7]. The construction of these instruments depends on heavily textual forms of information and this property may make it more appropriate and attractive for only a verbal type of learners.

The purpose of this study is to investigate the impact of using visual and active forms of information in the building or construction of the instrument that used to measure the learning preferences. As a result, the visual and active students are expected to respond strongly to these forms of information. Accordingly, this may affect the accuracy of detection their preferred learning style.

<table>
<thead>
<tr>
<th>No.</th>
<th>Learning style model</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VARK Learning Style</td>
<td>VARK Questionnaire (VARK)</td>
</tr>
<tr>
<td>2</td>
<td>Felder–Silverman Learning</td>
<td>Index of Learning Style (ILS)</td>
</tr>
<tr>
<td></td>
<td>Style</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Kolb Experiential Learning</td>
<td>Learning Style I inventory (LSI)</td>
</tr>
<tr>
<td></td>
<td>Theory</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Gregorc Learning Style</td>
<td>Gregorc Style Delineator (GSD)</td>
</tr>
<tr>
<td>5</td>
<td>Dunn – Dunn Learning Style</td>
<td>Productivity Environmental</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Preference (PEPS)</td>
</tr>
</tbody>
</table>
II. ASSUMPTION OF STUDY

Over the last few decades, a number of learning style instruments have been designed to help the learners to know their preferred learning style [6]. Although these instruments have seen a significant amount of statistical research in terms of validity and reliability, unfortunately in terms of investigating the impact of the content type this work is still in its infancy. Also, it is well-known that learning style models and instruments are built on the premise that students respond differently to the different forms of information. Accordingly, the researchers claim that the instrument itself should, therefore, also contain different forms of information. Since it is not known to what extent visual and active content of an instrument impacts on learning style measurement, more research is needed in this area.

III. LITERATURE REVIEW

Within the last four decades, a number of learning style models and instruments have emerged to help learners to know more about how they prefer to learn. Although all of these models and instruments have been designed based on the same premise, which is students respond and interact differently to the different forms of information, these models have different views as to the characteristics that should be adopted under the umbrella of learning styles [8, 9]. Table 2 summarizes the main differences among five well-known learning style models.

The consideration of learners’ learning style by providing different teaching approaches and curriculums has become an important pedagogical issue because only one teaching approach cannot fit all students and all instructional situations [6]. Therefore, a number of adaptive educational systems have been designed to accommodate the individual differences, most of these systems use the learning style instruments (mentioned in Table 1) to achieve the matching process between the teaching and learning style [2, 10].

In our research, we investigate the effect of using visual and active forms of information as content for construction the learning style instruments and the extent to which this will influence the measuring of the preferred learning style. In addition, we investigate the impact of using these forms of information on the time required for completing the instrument.

<table>
<thead>
<tr>
<th>Model</th>
<th>Concept of Learning Style</th>
<th>How many dimensions</th>
<th>Instrument</th>
<th>Cost</th>
<th>Instrument methodology</th>
<th>Type of content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felder–Silverman</td>
<td>“The characteristic strengths and preferences in the ways individuals take in and process information” [11]</td>
<td>5</td>
<td>Index of Learning Style (ISL)</td>
<td>Free</td>
<td>Select only one answer from two alternatives available for each question</td>
<td>Text only</td>
</tr>
<tr>
<td>VARK</td>
<td>“An individual’s characteristics and preferred ways of gathering, organizing, and thinking about information” [12]</td>
<td>2</td>
<td>VARK Questionnaire</td>
<td>Free</td>
<td>Select one or more answers from the four alternatives available</td>
<td>Text only</td>
</tr>
<tr>
<td>Gregorc</td>
<td>“Distinctive and observable behaviours that provide clues about the mediation abilities of individuals and how their minds relate to the world and, therefore, how they learn” [13]</td>
<td>4</td>
<td>Gregorc Style Delineator (GSD)</td>
<td>Not free</td>
<td>Rank-order group of items for each question</td>
<td>Text only</td>
</tr>
<tr>
<td>Kolb</td>
<td>“Generalized differences in learning orientation based on the degree to which people emphasize the four modes of the learning process” [14]</td>
<td>2</td>
<td>Learning Style I inventory (LSI)</td>
<td>Not free</td>
<td>Rank-order set of items for each question</td>
<td>Text only</td>
</tr>
<tr>
<td>Dunn-Dunn</td>
<td>“The way in which individuals begin to concentrate on, process, internalize, and retain new and difficult information” [6]</td>
<td>5</td>
<td>Productivity Environmental Preference Survey (PEPS)</td>
<td>Not free</td>
<td>Likert-type scale</td>
<td>Text only</td>
</tr>
</tbody>
</table>
IV. RESEARCH QUESTION

In this study, by comparing the preferred learning style of six students, and interview them, the researchers attempt to answer the following questions:

1. To what extent does using visual and active content in the instrument affect the measuring of preferred learning style?
2. What impact does the use of the visual and active content based instrument have on the time taken to undertake the detection?

This research is considered to be an important step determining the most appropriate learning style instrument and to avert the potential problems arising from a mis-measurement of learning style.

In particular, this research will help us to understand the impact of content (forms of information) that could be used to build instruments with improved precision of learning style.

V. METHODOLOGY

According to Cagiltay and Bichelmeyer [15], a phenomenon cannot be completely investigated by quantitative research alone, therefore in this research, qualitative research techniques are also used to examine the research question. The preferred learning style of six students has been measured using two different instruments, whereby, the students underwent both a developed instrument which was enhanced by visual and active forms of information and a VARK questionnaire which depends only on the textual form of information. The results of both approaches were compared and the researcher conducted six interviews with the participants about their preferred learning style and their opinion about the effect of using the visual and active content in the construction of learning style instruments.

VI. PARTICIPANTS

This research was conducted, with six participants, in a school of Science and Technology at Nottingham Trent University. Table 3 shows participants’ details.

<table>
<thead>
<tr>
<th>Coding name</th>
<th>Gender</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Male</td>
<td>24</td>
</tr>
<tr>
<td>P2</td>
<td>Female</td>
<td>24</td>
</tr>
<tr>
<td>P3</td>
<td>Male</td>
<td>27</td>
</tr>
<tr>
<td>P4</td>
<td>Male</td>
<td>26</td>
</tr>
<tr>
<td>P5</td>
<td>Male</td>
<td>25</td>
</tr>
<tr>
<td>P6</td>
<td>Male</td>
<td>25</td>
</tr>
</tbody>
</table>

P = Participant

VII. DATA COLLECTION

As mentioned the participants’ preferred learning style have been measured twice by using two different instruments and six interviews have been conducted. Audio records and field notes were used to collect data from each interview.

At the beginning of each interview, the researcher explained the purpose of this study and each participant was made aware of key issues related to the concept of learning style and their right to withdraw from the study. The interviews were semi-structured, since the sessions of the interview were not restricted to specific questions, and the nature of the interview was determined by participants’ response.

VIII. THE DEVELOPED INSTRUMENT

Visual and active format of information such as figures, graphs and formulae were used to construct the developed instrument which consists of sixteen items each with four alternative answers which correspond to the four learners’ types. These alternatives are given a priority level by the participants from (0 least important) to (3 most important) with the option of giving the same level of priority to more than one alternative. The score of each type is collected with the range being 0 to 48. This range can be divided into three levels which are mild preference (from 1 to 16), moderate preference (from 17 to 32) and pure preference (from 33 to 48). Table 4 presents an example question from the developed instrument.

<table>
<thead>
<tr>
<th>Q7: Which presentation style do you prefer?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pythagoras’ theorem states that the square of the hypotenuse (the side opposite the right angle) is equal to the sum of the squares of the other two sides.</td>
</tr>
<tr>
<td>Pythagoras’ theorem states that the square of the hypotenuse (the side opposite the right angle) is equal to the sum of the squares of the other two sides.</td>
</tr>
<tr>
<td>In right-angled triangles Square of the hypotenuse (c) equal the sum of the squares of the other two sides a, b. If ( c^2 = a^2 + b^2 ), then ( c = \sqrt{a^2 + b^2} ).</td>
</tr>
<tr>
<td>In right-angled triangles Square of the hypotenuse (c) equal the sum of the squares of the other two sides a, b. If ( c^2 = a^2 + b^2 ), then ( c = \sqrt{a^2 + b^2} ).</td>
</tr>
</tbody>
</table>

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IX. FINDINGS

A. Students’ preferred learning style

Table 5 shows the distribution of participants’ preferred learning style in each dimension based on both a VARK questionnaire and developed instrument. N=6.

For visual impact, this data can be displayed as shown in Fig.1. By comparing the number of students in each dimension we can see that there is a notable difference between the results of two instruments, for example, the developed instrument shows all of the participants (6 students) have a pure visual preference, whereas the results of VARK questionnaire suggests that no participant has a pure visual preference. These differences can be displayed visually in the Fig.1 below.

<table>
<thead>
<tr>
<th></th>
<th>Visual</th>
<th>Aural</th>
<th>Kinaesthetic</th>
<th>Read/Write</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure preference</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Moderate preference</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Mild preference</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

V= VARK.  
D= Developed instrument.

B. Participants’ perception of learning style

At the start of each interview, participants were made aware of their preferred learning style which was measured by the two instruments. The participants were asked about the importance of considering the individual differences among students in teaching methods. All of the participants indicated that the individual differences should be considered in teaching because only one teaching method cannot fit all students

“Teaching should always include everything; we cannot depend on only one method” (P5).

C. Impact of content on participants’ answers

For the majority of participants (five out of six) think that the new visual and active features of developed instrument affected their responses to the point where it altered the assessment of their preferred learning style.

"students understand the text differently” (P2). “these features will attract the whole class; it will also attract those students who are not more interested in learning” (P3).

Only one participant (P5) thinks that the answer will not be affected except.

“There is a possibility if someone does not understand English very well. Obviously, for them, the answers will be affected because they may miss something when there is complete text” (5).
D. Impact of content on time

The issue of time taken to complete the instrument was also investigated and the participants were asked whether they believe that the content of the instrument played any role in the time needed to finish the questionnaire. All of the participants stated that the visual and active content played a key role in reducing the time needed to complete the questionnaire.

(P1) “Defiantly, that is an effect, for example, if we don't know the mean formula we need to read and break down the text to extract the formula and that takes time and may get confused sometimes”.

(P5) “I prefer both (visual and verbal forms) but when I see the things I can understand more quickly than reading … the only difference is the complete text one takes the time to understand the question first of all, but as soon as I see a formula or graph I will get the idea. So the answer will not an affected but time will be affected”.

X. DISCUSSION

The findings of this research provide new insights into the impact of an instruments’ content on the measurement of learning styles which are widely used in adaptive education systems.

This qualitative study investigated the impact of using the visual and active content to build the learning style instrument. Generally, the findings indicate that the different forms of content have a considerable impact on the measurement of learning style and the time needed to complete the questionnaire.

The results of this study showed that the number of students who classified as a “pure visual type” is increased significantly when they used the developed instrument which contains visual forms of information. This result may be interpreted by the fact that visual type of learners responds strongly to the visual content such as (pictures, charts, figures … etc.).

In contrast, the number of “pure aural students” and “pure read/write students” have not seen any significant differences. This result may be explained by the fact that the both instruments use the same forms of information to present the questions that related to these types of learners (Aural, Read/Write).

The main implication of this study is that the result of measuring the learning style could be changed according to the type of instruments’ content. Therefore, it is critical to design and build our teaching and adaptive education systems based on the outcomes of learning style instruments which depend on only one form of information.

XI. LIMITATION

The main limitation of this research was the small number of participants. It is clear that we cannot generalize the results based on a sample of six students especially as they are studying at the same course in the same university and only one participant (out of six) is female. For this reason, further research with a greater number of participants from different universities and courses is needed.

XII. CONCLUSION

The results of this study indicated that there is a need for more investigation in terms of the impact of instruments’ content type on the measuring of learning style. Since we know that these instruments have used by a the most of adaptive educational systems for the purpose of matching the teaching style with students' preferred learning style [3]. Accordingly, it is important to investigate to what extent these instruments measure what we think is being measured before we build a teaching approach based on them.

REFERENCES


A Multi-criteria Methodology to Select the Best Wave Energy Sites

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Abstract—This paper presents a methodology to choose the best locations for wave energy projects around the coast. It is based on a multi-criteria assessment methodology that considers physical, environmental and socioeconomic constraints. The proposed decision making tool can be customized by the final user according to different systems and implementation conditions. A set of factors (wave energy criteria, bathymetry, distance to coastline and ports, seabed …) are considered for the final selection. The tool is tested over a large area. It can also be used for a specific area, if sufficient geospatial data are available with good accurate spatial resolution. The methodology is applied to the French Atlantic coast. Brittany and the south western of France are most suitable for wave energy devices deployment.

Keywords—Wave energy, Decision making system, Geo-spatial multi-criteria analysis, Geographic Information System (GIS)

I. INTRODUCTION

The location choice for wave energy farms depends on the assessment of a number of criteria [1]. Geo-spatial multi-criteria analysis is very suitable to consider a wide variety of environmental and administrative factors (e.g. water depth, distance to shore, geology, …). There are many applications in the literature where GIS (Geographic Information System) techniques are combined with multi-criteria analysis [2-8]. Nobre et al. [1] developed a geo-spatial multi-criteria analysis for wave energy converters deployment in Portugal. Carver [9] presents an application for researching suitable places to store radioactive wastes in UK. Our study paper aims at designing a tool for wave energy conversion (WEC) system deployment. This method will select an appropriate location minimizing technical constraints. As there is not a main focus on a WEC system, users must consider the intrinsic characteristics of the WEC (e.g. optimal wave energy and height, mooring depth) and, hence, estimate the impact for each factor.

This paper is organized as follows; first, methodology is described. Then, criteria for site selection are discussed and detailed. A step by step description of the methodology is afterwards written. Results are finally presented and discussed.

II. METHODOLOGICAL APPROACH

The methodology is shown figure 1. First step will select the study area and create the analysis mask according to a set of criteria. All remaining steps will then be performed within this masked area. Main factors related to wave energy farms deployment are then identified. Once all criteria are defined, a common evaluation scale must be set. This procedure is well known as “reclassification”.

![Figure 1. Methodology for multi criteria decision](image)

Afterwards, factors are weighted. Geospatial analysis is then used to calculate the overall suitability matrix for implementing the WEC. This matrix will have values between 0 and 100, where highest value represents the most suitable places. A set of parameters are defined as exclusion areas (marine protected areas; five hundred meters zone from cables; shipping lanes, depths between 20m and 200m). Finally, features for selection criteria are: distance to coastline, distance to ports; distance to the electric network; seabed; wave power (significant height and power). The multi-criteria analysis of this study needs some testing procedures in order to assess the impact of each selection criterion on the final result. Implementation of a routine using a geo-processing model makes the system testing and calibration efficient. A processing model has been created. The inputs of the model are data layers gathering the main criteria for site selection. The tools, such as buffering and intersection or union operations are represented in yellow (Figure 2). Finally, the output layers or intermediate outputs
are represented in green. The first processing model creates the analysis mask (i.e. study area_20_200m).

![Image](image1)

Figure 2. Final output for decision-aid system for wave energy sites selection

III. RESULTS AND DISCUSSIONS

Best sites for wave energy extraction are in the south west of France and Brittany (Figure 3). The multi-criteria methodology does not consider types of wave energy system. After, developers have to install the adequate devices. In wave shadowed areas, most suitable sites are far from the coast. For instance, in some areas such Vendée, or Charente-Maritime,…. best location is at approximately 50 km far from the coast.

![Image](image2)

Figure 3. Best areas for onshore wave energy devices deployment on the French Atlantic coast

This is due to the coastline orientation compared to the incident wave direction as well as the seabed slope (bathymetric constraint as depth has to be higher than 20m). These locations are, by nature, not efficient for wave energy conversion because the combination of the most frequent wave directions and shore location creates shadow zones. Moreover, for economic, technical and operational reasons (e.g. connection to the power grid, operation and maintenance), wave energy converter has to be as close as possible to the coast. Areas deducted by our tool fit very well with real projects in France such as SEM-REV experimentation offshore Le Croisic, test site in the Audierne bay in Brittany.

IV. CONCLUSIONS

This paper presents a methodology to choose the best locations for wave energy projects around the coast. The most suitable places are located in the Atlantic coasts in the south west of France as well as in Brittany, where the highest wave energy resources and minimums constraints are observed. The methodology proves that it can be of general use. But reclassification and weighting procedures must be calibrated for any specific wave energy system and areas of interest. A major output of this technique is the evaluation of the economic potential.

V. ACKNOWLEDGEMENTS

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Comparative by simulating the eventual waste generation of building indoor pavements construction

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Abstract The construction sector affects the environment through CO2 emissions generated by use of massive quantities of materials, energy, and waste during the construction and demolition process. Moreover, current technology offers a wide variety of materials, products and construction systems that could be used for a similar solution; however, the decision to select one or other element lies with the price and then by regulatory requirements and availability (ignoring the issue of sustainability). In an apartment building, the pavements are one of the elements with major representativeness and more possibilities of alternative variables in its materials; so, this research expose three different types of pavements with similar prices, comparable functions, and normative compliance, but providing a new sustainable perspective: The construction and demolition waste (C&DW) analysis. The results (simulation of waste) evidence the differences between the wastes generated from each type of pavement, pointing that the application of sustainable management criteria can be significant for sustainable buildings construction. This research shows a new criterion applicable to the construction sector that could improve the selection (with equal requirements) of one type of pavement into a more environmentally friendly pavement, allowing the achievement of profits for the builders.

Keywords-building pavements; material selection criteria in construction; selection of sustainable materials; sustainable construction; waste simulation

I. INTRODUCTION

Currently, one of the biggest challenges facing the planet is caused by waste generation and their accumulation in landfills, being the construction and demolition waste (C&DW) the most representative [1].

In a building, different construction phases arise including the execution of pavements; which are considered as the elements with the larger horizontal surface, being one of the main causes of C&DW [2]. In this research, the wastes generated (construction and eventual demolition) by three types of usual interior floors in Spain are analyzed, compared and quantified through simulation. The basic objective of this research is to establish and identify which type of pavement generates more wastes, what are they and what relationship maintained between them.

Three types of pavements were applied in the same case study (multi-family housing located in Barcelona, with a pavement total area of 2,341.00 m2): The constructive application was equivalent and with comparable feasibility of use; the selected pavements were: Indoor terrazzo tile (P1), ceramic rustic tile (P2) and Spanish granite tile (P3).

We used the Net Waste Tools software (NWT) (with the data of the selected pavements) as a simulation tool, this allowed us to obtain reports for each pavement type, finally, these reports were standardized to make a comparison. The results indicated that, although the analyzed pavements could be used (solving the technical requirements, regulations, difficulty of construction and similar prices), their estimated waste generation is not the same for all of them, enabling us to highlight that this type of analysis can perceive differences which have passed unnoticed by the construction sector so far, with an additional contribution to be a new approach that promotes sustainability, environmental care and financial savings for the sector.

II. BODY OF KNOWLEDGE

It is expected that the world population growth will double before the middle of this century, accentuating in urban and surrounding areas. If we take into account the limitations of building areas in big cities, the building sector seems to be forced to define new solutions to this problem [3] and the validation of building systems for sustainable housing, could help in this regard. Between the different elements in a building construction, the indoor pavements have not yet been linked optimization criteria for its sustainable ratification (despite exist variety of systems and similar constructive solutions); While it is true that the use of more complex systems (diversity of materials and construction processes of placing wet) may be less sustainable than those using less diversity of materials, and putting in work it is simpler.
In Spain, during the period from 1990 to 2007, housing construction, urbanized areas and infrastructure came to report an increase of 40%, which led to an increase in material consumption over 141% in that period [4] (including pavements).

Moreover, the sustainable development and thus the sustainable construction has become an increasing concern to the globe, through the comprehension of the contamination effects over the environment. In the United States, building sector represents 38.9% of the primary energy consumption, 38% of all CO2 emissions and 30% of waste generation [5]. In the European Union (EU) building construction consumes 40% of primary energy, 40% of all materials and generates 40% of wastes [6].

The EU report nearly 450 million of tones per year, only 25% of which are retrievable [7]. Whereas in Spain, it is estimated that 70% corresponding to wastes from activities related with C&DW [6]. In addition, CO2 emissions in the residential, commercial and institutional sectors report an increase of 65% in comparison with 1990 [8].

With respect to the foregoing, it is important to emphasize that building indoor pavements represents a contrasting environmental impact. Housing buildings, particularly indoor pavements should be evaluated by comparable criteria that will allow its apocryphal pounding on waste generation and recycled material used for its process with an adequate construction system.

In Spain [9], the construction sector produces around 40 million tons of residues, reaching 32% of the total volume; if the previous hypothesis refers to uncertainty which presents the C&DW of different building pavements generation was verified, it could be argued and contribute to savings in raw materials, conservation of natural resources, environmental preservation, protection of public health, the use of recycled material [10], waste reduction and in the wider context, to sustainable development. Therefore, the sustainability on construction could bring new solutions to current society paradigms; one of these could be the establishment of new environmental criteria (minimum C&DW generation) on the constructive systems (indoor pavements), that satisfying the normative or the operational use criteria but being sustainable at the same time.

III. ELEMENTS, MATERIALS AND METHODS

The case study (41°24'17.6"N 2°10'12.8"E) is located on a lot of 705.60 m2 of which 346 m2 are buildable. The building counts with 34 houses and one commercial unit on the ground floor. Floors are distributed as follows: One basement, a ground floor and eight floors type (four apartments by floor) and upper attic (two apartments). The type-apartment has the following distribution of spaces: Living/dining room, kitchen, four bedrooms, bathroom and separate WC and sink (See Fig. 1).

Figure 1. Distribution of spaces.

The pavements of the study correspond to the total communal areas and housing; for each type of use, a type of pavement was selected which complies with the requirements of the Spanish regulation (SU1 Security against the risk of falls, and DB-SUA utilization and accessibility Security; by the CTE Technical Code of the Edification).

Figure 2 shows geometry and configuration per square meter of pavement, the materials and surface thickness defined in the simulating waste analysis are the following: Indoor terrazzo tile (P1), ceramic rustic tile (P2) and Spanish granite tile (P3).

For each pavement, quantification by square meters of the prices, yields, loss of waste, packaging materials and densities used in the simulation were obtained from the database: Prices of construction generator by the CYPE S.A.V. 2015i software (www.cype.com). Table 1 shows the headings of each pavement, indicating specific quantities and prices of inputs materials that were used in the simulation.

![Figure 2. Geometry and configuration per square meter of pavement.](image-url)
**TABLE I. DESCRIPTION OF PAVEMENTS**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Performance</th>
<th>Unit price</th>
<th>Item price</th>
</tr>
</thead>
<tbody>
<tr>
<td>m²</td>
<td><strong>P1 (Terrazzo flooring)</strong>. Tile flooring terrazzo medium grain (6 to 27 mm), classified normal use for indoor, 40x40 cm, beige, positioned at blow pot on a bed of cement mortar, industrial, M-5, and grouted with white cement grout BL-V 22.5 colored with the same tonality of the tiles.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m³</td>
<td>Water</td>
<td>0.011</td>
<td>1.50</td>
<td>0.02</td>
</tr>
<tr>
<td>t</td>
<td>Industrial mortar for masonry, of cement, grave, class M-5 (compressive strength 5 N/mm²), supplied in sacks, according to UNE 998-2.</td>
<td>0.060</td>
<td>32.25</td>
<td>1.94</td>
</tr>
<tr>
<td>m³</td>
<td>Indoor terrazzo tile, normal use, medium grain (6 to 27 mm), nominal 40x40 cm, beige colour, with a first polishing in factory, for polishing and buffing final in work, according to UNE-EN 13748-1.</td>
<td>1.050</td>
<td>10.25</td>
<td>10.76</td>
</tr>
<tr>
<td>kg</td>
<td>White cement BL-22.5 X, for paving, in sacks, according to UNE 80305.</td>
<td>1.000</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>kg</td>
<td>Grout colored with the same tonality of the tiles, for terrazzo paving.</td>
<td>0.500</td>
<td>1.15</td>
<td>0.58</td>
</tr>
<tr>
<td>h</td>
<td>Official 1st welder.</td>
<td>0.192</td>
<td>17.24</td>
<td>3.31</td>
</tr>
<tr>
<td>h</td>
<td>Assistant welder.</td>
<td>0.354</td>
<td>16.13</td>
<td>5.71</td>
</tr>
<tr>
<td>%</td>
<td>Auxiliary resources</td>
<td>2.000</td>
<td>22.46</td>
<td>0.45</td>
</tr>
<tr>
<td>%</td>
<td>Indirect costs</td>
<td>3.000</td>
<td>22.91</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td><strong>Ten-year cost of maintenance: 2,12€ in the first 10 years.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total:</strong></td>
<td></td>
<td></td>
<td>23.60</td>
</tr>
<tr>
<td>m²</td>
<td><strong>P2 (Ceramic tiles flooring with cement as a bonding material)</strong>. Ceramic tile flooring rustic tile, 3/2/H/−30x30 cm, 15.13 €/m², received with white cement mortar BL-II/A-L 42.5 R M-5 of 3 cm thick and grouted with cementitious mortar joints with high resistance to abrasion and reduced water absorption, CG2, for minimum joint (between 1.5 and 3 mm), with the same tonality of the pieces.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m³</td>
<td>White cement mortar BL-II/A-L 42.5 R, type M-5, made on site with 250 kg / m³ cement and a volume ratio 1/6.</td>
<td>0.030</td>
<td>88.34</td>
<td>2.65</td>
</tr>
<tr>
<td>m²</td>
<td>Ceramic tile rustic tile 3/2/H−, 30x30 cm, 15.13 €/m², according to UNE-EN 14411.</td>
<td>1.050</td>
<td>15.13</td>
<td>15.89</td>
</tr>
<tr>
<td>kg</td>
<td>Cementitious mortar joints with high abrasion resistance and reduced water absorption, CG2, for minimum joint between 1.5 and 3 mm, according to UNE-EN 13888.</td>
<td>0.100</td>
<td>0.99</td>
<td>0.10</td>
</tr>
<tr>
<td>h</td>
<td>Official 1st welder.</td>
<td>0.273</td>
<td>17.24</td>
<td>4.71</td>
</tr>
<tr>
<td>h</td>
<td>Assistant welder.</td>
<td>0.137</td>
<td>16.13</td>
<td>2.21</td>
</tr>
<tr>
<td>%</td>
<td>Auxiliary resources</td>
<td>2.000</td>
<td>25.56</td>
<td>0.51</td>
</tr>
<tr>
<td>%</td>
<td>Indirect costs</td>
<td>3.000</td>
<td>26.07</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td><strong>Ten-year cost of maintenance: 4.56 € in the first 10 years.</strong></td>
<td></td>
<td></td>
<td>26.85</td>
</tr>
<tr>
<td>m²</td>
<td><strong>P3 (Natural stone flooring with cement mortar as a bonding material)</strong>. Granite tile flooring Grey Villa, interior, 60x40x2 cm, flamed finish, received with cement mortar M-5 and grouted with cementitious mortar joints, CG1, for minimum joint (between 1.5 and 3 mm), with the same tonality of the pieces.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m³</td>
<td>Cement mortar CEM II/B-P 32.5 N type M-5, made on site with 250 kg / m³ cement and a volume ratio 1/6.</td>
<td>0.032</td>
<td>115.30</td>
<td>3.69</td>
</tr>
<tr>
<td>m³</td>
<td>Spanish granite tile, Grey Villa, 60x40x2 cm, flamed finish, according to UNE-EN 12058.</td>
<td>1.050</td>
<td>30.05</td>
<td>31.55</td>
</tr>
<tr>
<td>kg</td>
<td>Cementitious grout, CG1, for minimum joint between 1.5 and 3 mm, according to UNE-EN 13888.</td>
<td>0.150</td>
<td>0.70</td>
<td>0.11</td>
</tr>
<tr>
<td>h</td>
<td>Official 1st welder.</td>
<td>0.314</td>
<td>17.24</td>
<td>5.41</td>
</tr>
<tr>
<td>h</td>
<td>Assistant welder.</td>
<td>0.314</td>
<td>16.13</td>
<td>5.06</td>
</tr>
<tr>
<td>%</td>
<td>Auxiliary resources</td>
<td>2.000</td>
<td>26.07</td>
<td>0.78</td>
</tr>
<tr>
<td>%</td>
<td>Indirect costs</td>
<td>3.000</td>
<td>46.74</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td><strong>Ten-year cost of maintenance: 4.33 € in the first 10 years.</strong></td>
<td></td>
<td></td>
<td>48.14</td>
</tr>
</tbody>
</table>

a. According to CYPE S.A.V. 2015i software.
The above data were implemented in the NWT tool that allows designers, builders and contractors to increase the efficiency of use of materials and comply with legislation of its management; since this, quantifies and determines the type of waste, evaluates the use of resources, cost reports and quantities of waste to generate and provides comparative strategies.

IV. RESULTS AND DISCUSSION

Figure 3 shows the results from NWT, partial expressed in percentages of each pavement studied in tones and grouped according to the European Waste Catalogue (CER).

![Figure 3. Waste components generated on each pavement.](image)

Both for P2, as to the P3, only two materials are expected to generate: concrete in both cases; and ceramic, stone and land, respectively. Finally, for the P1 are expected to have: concrete, concrete and ceramic combination and borated. In all three case studies, the material is always present is the concrete (with average values of 14%); however, the most representatives (average of 85%) are ceramic materials or mixtures thereof with other, reflecting the difficulty of a single feasible segregation (P2 except that produce not combined ceramic).

With respect to the evolution of possible implications during the construction of the study cases through a standard or conventional (without sustainable criteria) waste management and a desirable or ideal waste management (with sustainable criteria); and implementing as a normalization criteria of data, the selected variables according to the size of the tile (a), the construction cost (b), and the amount of tiles per square meter (c). Figure 4 shows to the comparative studied pavements (for a1, b1 and c1 per tones and cubic meters respectively, and for a2, b2 and c2 per value of waste generated respectively).

In the case of a1, b1 and c1, the waste generated by the P3 are the most volume and weight producer (Concrete and ceramic materials mix), also in the three cases, the standard management produce significantly more waste when compared with the desirable management. And finally, the unit of cubic meters proves to be the most representative form of measurement. Of these three graphs, standardization criteria that best allows us to discern the behavior is the size of the tiles (highest numerical scale in the vertical axis).

In terms of a2, b2 and c2, the waste which presents the highest value varies according to the normalization criteria: for a2 is the P2 (ceramic materials), for b2 and c2 is the P1 (land, stones and others); considering the amount of tiles per square meter like the most sensitive criterion of normalization of the three cases. Moreover, in all cases the standard management always generate more wastes than the desirable management.

V. CONCLUSIONS

This paper shows that the establishment of waste minimization techniques and an adequate management, brings financial benefits for the construction and environmental benefits for the site, because avoid unnecessary materials use and generate less waste during the execution process; which was particularly evidenced by the differences in prices and volumes of the “desirable” and “standard” C&DW management (by the NWT simulation).

![Figure 4. Desirable and standard management of the pavements according to: a) size of the tile; b) construction cost; c) amount of tiles per square meter.](image)
Option P3 was the most expensive in terms of management, followed by option P2 and finally P1. The cost difference between P1 and P2 is not significant. But P3 is exceeded by more than double the material and construction cost of the P1.

The total cost of recycling indoor pavement materials turned out to be more in a “standard” management than in a “desirable” (given that in standard management it is not widely applied minimization techniques). This “desirable” management cost was found in cases with a negative value because the value of the incorporation of recycled and reused materials in the construction is greater than the value of waste disposed of; therefore, the total cost of recycling is zero (earn a profit).

The option P1 has the most negative value, that means that the option could have the lower recycling cost due to their high recycle content concerning other options; therefore, there is a better chance of recovering materials. In the case of obtaining waste reduction performance, the highest occurred on option P3 with 26.61% on tons of waste reduction and 38.53% on containers cost reduction, in spite of the increase in the value of recovered materials only became to 10%.

Moreover, the reduction of the types of waste in a desirable management over a standard it is of 37.50% in all cases (weight, volume and cost); it, therefore, be argued that the application of waste minimization techniques and the establishment of an appropriate waste management will generate economic and environmental benefits, given that the tones of materials intended for landfill, the volume that they occupy, and the cost will be less.

Weight and Volume of the tiles were the best parameters than describe and allows the establishment of the correlations between different variables, being prescribed like the decision parameters for the final election between sustainable indoor pavements.

Different types of generated waste on simulation were grouped into two areas: Tiles materials and concrete; tiles materials have the highest quantity of waste. The common material in the three options was the concrete, reaching rates with respect to the rest of materials of a 15% for the P1 and P2, and an 11% for the P3.

Analyzing the construction systems studied, it was observed that P1 generates the largest quantity of wastes (greater thickness and hence higher weight and volume); while the P2 (thinner tile and mortar) reports the least amount of waste weight and volume. This denotes that the volume and density of materials (tiles and concrete) influence the generation of waste material.

Finally, although the P3 is a natural stone and Spanish legislation recommends this pavement to be considered for use in any space, in this research, it turns out to be that higher cost is in construction and lower percentage of recovery of materials can reach (caused by the manufacturing process); but on the other hand it is the one that gets a higher yield by applying a "desirable" management of waste (by weight and volume).

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REFERENCES


Workshop
Doctoral Workshop: Sustainable Development Conceptualisation

Main Area of Focus: Validity and Reliability of Research Findings

Workshop Presentation and Modalities

- Discussion and presentation will be on the factors to be considered in research design to achieve valid and reliable research outcomes/findings;
- Typical examples and case studies will be drawn;
- All participants will be involved in the discussions fora;
- Possible problems to robust research findings will be unfolded;
- Solutions to achieve research findings without much stress will be highlighted;
- Sequence to achieve valid research outcomes will be drawn.

Organiser: Julius Ayodeji Fapohunda
Cape Peninsula University of Technology (CPUT), South Africa
Poster
High Voltage Pulses to Recover Copper from Waste Printed Circuit Boards

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Abstract - Electronic waste (e-waste) is one of the rapidly growing solid waste streams around the world. Advancement in technology, increase in usage of electronic products and rise in population during the last decade is causing the rapid obsolescence of e-waste. E-waste generation is around 40 million tonnes each year and increasing at the rate of 3-5% per annum. E-waste is heterogeneous in nature and contains both valuable and hazardous materials. Printed circuit boards (PCBs), a key component is used in most of the electronics and contributes 3% by weight to the total e-waste. PCBs contain copper and gold 20 times more than their respective ores hence various physical, chemical, electrostatic, pyrolysis and metallurgical techniques are investigated to recover copper. But due to disadvantages such as (a) release of toxic gases during crushing (b) non-selective fragmentation between metals and non-metals (c) use of chemicals or acids (d) high energy utilization demands the environmental friendly and sustainable technique to recover copper from waste PCBs. In this study, we have used high voltage pulse technology to recover copper from waste PCBs. To achieve high recovery, operating conditions such as voltage and number of pulses were optimised. The results signify that applied electric voltage and number of high energy pulse were the important factors to segregate copper from waste PCBs. Reduction of noxious gases, high recovery of copper and negligible mechanical damage were the advantages of using high voltage pulse technology to recover copper from waste.

Keywords: Electronic waste; Waste PCBs; High voltage pulse; Copper; Eco-friendly process
Many thanks for your participation and we hope to see you next year…!

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