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August 28, 2024

Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2021) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

The 1st International Conference on Smart Mobility and Logistics Ecosystems (SMiLE)

September 17-19, 2024, KFUPM, Saudi Arabia

Technology readiness level assessment on digital technologies for energy efficiency

Elang Pramudya Wijaya[a,b,*], Muhammad Asif[c]

[a]Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia
[b]Department of Mechanical and Biosystem Engineering, IPB University, Kampus IPB Dramaga Bogor 16680, Indonesia
[c]Architectural Engineering and Construction Management Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Abstract

Digitalization offers the potential to increase through new/developed technologies that can gather and analyze datasets then use it to improve or change the physical behavior of indoor or outdoor environments either automatically or through human intervention. Technologies are evaluated and compared based on the nine parameters on the TRL. The Technology Readiness Level (TRL) assessment is based on the type and size of the entity developing the technologies. This study presented an approach to measuring TRL on digital technologies related to building energy efficiency. An expert survey assessed the technology readiness level in buildings energy efficiency digital technologies. This paper contributes to the widening and systematizing of knowledge on the maturity and understanding digital technologies related to energy efficiency. This study aims to inform researcher, user, and industry to support energy efficiency technology development focusing on digital technologies.

Keywords: Technology readiness level, Energy efficiency, Digital technologies, sustainable buildings;

1. Introduction

Most population lives in urban areas. The latest report from the United Nations (UN), the urban population reached 4.2 billion in 2018 (Nations, 2018). The growth in urban population will continue to rise which is taking place in

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: g202214140@kfupm.edu.sa

developing countries such as India, Indonesia, and African countries. Urbanization which refers to the expansion of the population living in urban areas has many challenges. Since the city is regarded as the center of economic growth, peoples from rural areas tend to come to the city to seek a better life. By 2050, the global population will increase and reach 9.7 billion, and 68% of the population will live in cities (Sun et al., 2020). New buildings are under construction to accommodate the need of housing for newcomers. To overcome this problem, expand the urban areas or make the city denser (densification) (Höjer & Mjörnell, 2018). New buildings mean adding energy consumption for the region (Wijaya & Yatim, 2021). This will increase greenhouse gas emissions while we have to ensure security of energy supply. Buildings are responsible for almost 45 % of overall energy consumption and releasing 36 % CO2 emissions in the EU region (Economidou et al., 2011), and primarily old buildings will consume more electricity than newer buildings. One of the solutions for reducing total energy consumption is renovating the existing buildings and adding new technologies. This will potentially reduce total energy consumption by 5 % (Bahar et al., n.d.; Economidou et al., 2011).

Nowadays, property investors consider energy efficiency for better profit. Also, green building certification will be mandatory for new buildings. There are several reasons why property investors in adopting sustainable investment in their strategies. Building consumer also plays an important role in succeeding sustainable campaigns with their adaption and awareness to the new technologies. Despite the investment would cost someone in adopting building technologies, this will benefit the building owner in the long run. Energy efficiency will decrease their electricity consumption, resulting in reduced electricity bills, a longer age of electronic goods, and maximizing energy efficiency behavior. The technologies will help building owner to monitor electricity consumption, remote shut-off, etc. Energy market is in the transition phase to accommodate the latest technological advancements. Apart from these technological advancements, there are still no measurement tools related to these. The problem is that we do not know the stages of these advancements or what phase we are in.

In the shift from the industrial revolution to the information revolution has changed existing paradigms. The information can be used to several applications, such as decision-making, policy-making, leveling, and assessment. The information revolution has given way to a digital revolution impacting every aspect of business, especially buildings. Digitalization of real estate and buildings is based on decentralized energy storage, power generation, power distribution, and installation of networks and adding values with newer applications for residence or building management (Konhäuser, 2022). Konhauser et al state that basic for the digitalization of buildings is connectivity by monitoring and optimizing energy consumption which can be stated as smart building (Konhäuser, 2021). Words 'Digitalization' refers to converting physical format to a digital format which can be stored as data for future productivity or monitoring in a system (Verma et al., 2020).

Digitalization offers the potential to increase through new/developed technologies that can gather and analyze datasets then use it to improve or change physical behavior of indoor or outdoor environment either automatically or human intervention. Data gathering technologies such as sensor or smart meters to collect data on energy use and other conditions can affect energy use (occupant, appliances, and climate). Furthermore, data processed into useful information through data analysis by digital technologies such as machine learning, Artificial Intelligence algorithms. Then the processed data will be sent to devices to manipulate it that can affect physical change to optimize energy saving. Some devices use human interaction to change physical interaction such as mobile apps that can turn off the lamp. But, nowadays, devices have become more intelligent and can change automatically.

There have been several research on determining technology readiness level of technologies. Rybicka et al assess composite recycling technologies based on literature review (Rybicka et al., 2016). Also, Beims et al examine the development of thermochemical conversion process focusing on pyrolysis using the same method (Beims et al., 2019). The TRL assessment is widely used for developing/developed technologies. Baron et al use it to enable information on evaluating processes on advanced fuel cycles (Baron et al., 2019). Ma et al uses expert review to determine TRL for 3D concrete printing technologies (Ma et al., 2022). Several ways to examine the development of technologies by scaling the TRL level are literature review, expert survey etc. The assessment included most of the relevant articles and patent published, dividing it into the level of determined scale. This will provide insight to the assessment that still need to be addressed. Despite a large number of research studies which use TRL to assess the readiness level, but still very few studies that focused on broad building technologies.

This paper focuses on applying technology readiness level assessment to building digitalization, which will intersect with energy efficiency. This paper aims to trigger eco-innovation while reducing environmental effects and enhancing resilience to environmental pressure, achieving more efficient and responsible energy use.

Nomenclature

A	radius of
B	position of
C	further nomenclature continues down the page inside the text box

2. Methodology

Search for the terms "Technology readiness level assessment," "Digital technologies in energy efficiency", "Digitalization on energy infrastructure", "Energy Efficiency" with a few databases for studies from January 2020 to December 2022. Additional keywords that put on the list are "BIM", "Internet of Things (IoT)", "Digital Twin", "Virtual Sensing", "Artificial Intelligence (AI)", and "Machine Learning or Deep Learning". Major databases was in ScienceDirect, and Web of Science. The searches were delivered on keywords, abstract, and articles title. The result fell into several categories: technical papers, case study, scientific publications, and reports that published by an organization.

Fig. 1. Methodology of TRL assessment.

The technologies are assessed with focus on technology readiness parameter. The assessment also complemented with expert interviews. Technologies are evaluated and compared based on the nine parameters on the TRL. The Technology Readiness Level assessment is carried out based on the type and size of the entity developing the technologies. The lower value of TRL is for the technologies that have only been developed at the academic level. Higher TRL refers to small to large-sized company with their prototype or ready digital technology, which have the potential to scale up. The highest TRL score is on the technologies developed by large companies with significant research and development resources that already meet the commercial standard or are in commercialization.

Table 1. Framework for assessing the Technology Readiness Level (Solis & Silveira, 2020).

Technology developer	Comment	TRL
Large sized company	In development/ in commercial operation	8-9
Small/medium sized company	Successfully sold/ in commercial operation	8-9
Small/medium sized company	In development	4-7
R&D centre/university		1-5

3. Importance of Energy Efficiency in Buildings

Recent digital innovations offer new ways of solving energy efficiency issues, improving easier usability and performance of such systems. Technologies are facilitating new opportunities for digitalization and digital innovation, such as Building Information Modelling (BIM), Artificial Intelligence (AI), Internet of Things (IoT), Machine Learning, Digital Twin, and Virtual Sensing, etc. These technologies are transmitting and distributing new businesses which can deliver and consume energy in a a sustainable way (Verma et al., 2020). Innovative technologies mentioned above can provide ongoing businesses more revenue by optimizing the process, flexibilities and efficiencies.

In the building sector, literature reviews have been reported in recent years, and usually focused on the intelligent building systems, application, and automation using data-driven from machine learning and big data technologies.

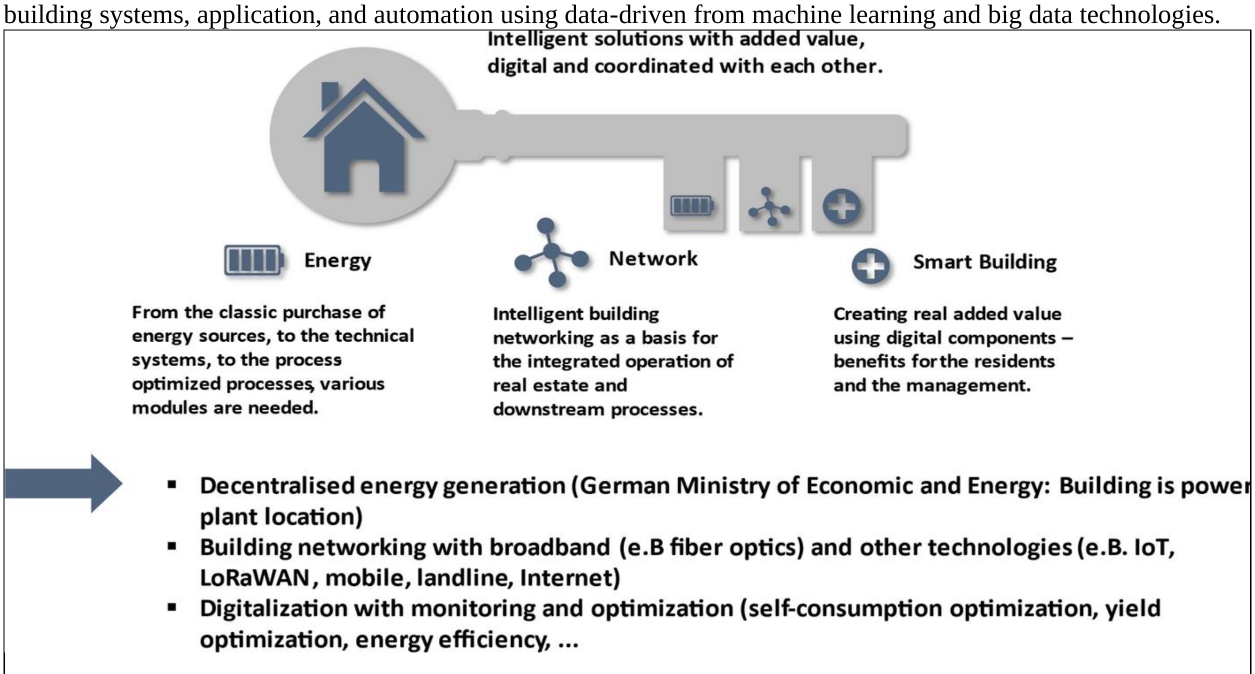

Fig. 2. Basic digitalization for real estate (Konhäuser, 2021).

Digital technologies are already widely used in all energy end-use sectors. New residential and commercial building are adopting digital technologies with smart appliances and intelligent energy management systems. The industrial sector has already adopted technologies aiming to increase the interaction between automated, connected, electric, and shared (ACES) mobility, shaping future energy consumption and bringing more money to the industry. However, the connectivity benefits of digitalization allow digital technologies to increase end-use efficiency and the efficiency of energy systems.

4. Technology Readiness Level (TRL)

Technology Readiness Level is a framework which provide measurement of technology maturity from basic principles (idea) to commercialization. TRL can be adapted to support understanding of product development at different stages of development (Rybicka et al., 2016). TRL have a wide variety of uses in systems, product development, and project management. Williamson et al. (Williamson & Beasley, 2011) TRL framework as listed in Table 2.

Table 2. Technology Readiness Level *[15]*.

TRL	Description
9	Actual system “flight proven” through successful mission operations
8	Actual system completed and “flight qualified” through test and demonstration
7	System prototype demonstration in a space environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed/reported

Another TRL scale developed by Graettinger et al. (Graettinger et al., 2002) shows that TRL can be implemented not only in hardware, but also in the software or systems. The scales also ranged between 1 (lowest level of readiness) to 9 (mature development). For example, a technology that assessed have a TRL 1 is by definition at the lowest level. After some development, the TRL value will increased and reach TRL 9, it has progressed through formulation of an initial concept for application, proof of concept, laboratory testing, environmental testing, then integration into a system, and the last is proven and qualified. depends on the progress of the hardware/software development. The TRL matrix is listed on appendix 1.

5. Digital technologies overview

5.1. Internet of things (IoT)

The Internet of Things has grown and become the most used system in the building applications. It consists of a collection that connects physical devices that are linked together by sensors, applications, and other technologies for integration and data exchange across devices and systems (Shah et al., 2022). IoT application in smart buildings to control and monitor lighting, heating, ventilation, and air conditioning. Smart monitoring and control presented by IoT systems can limit power consumption in unoccupied building zones, detecting and diagnosing troubles.

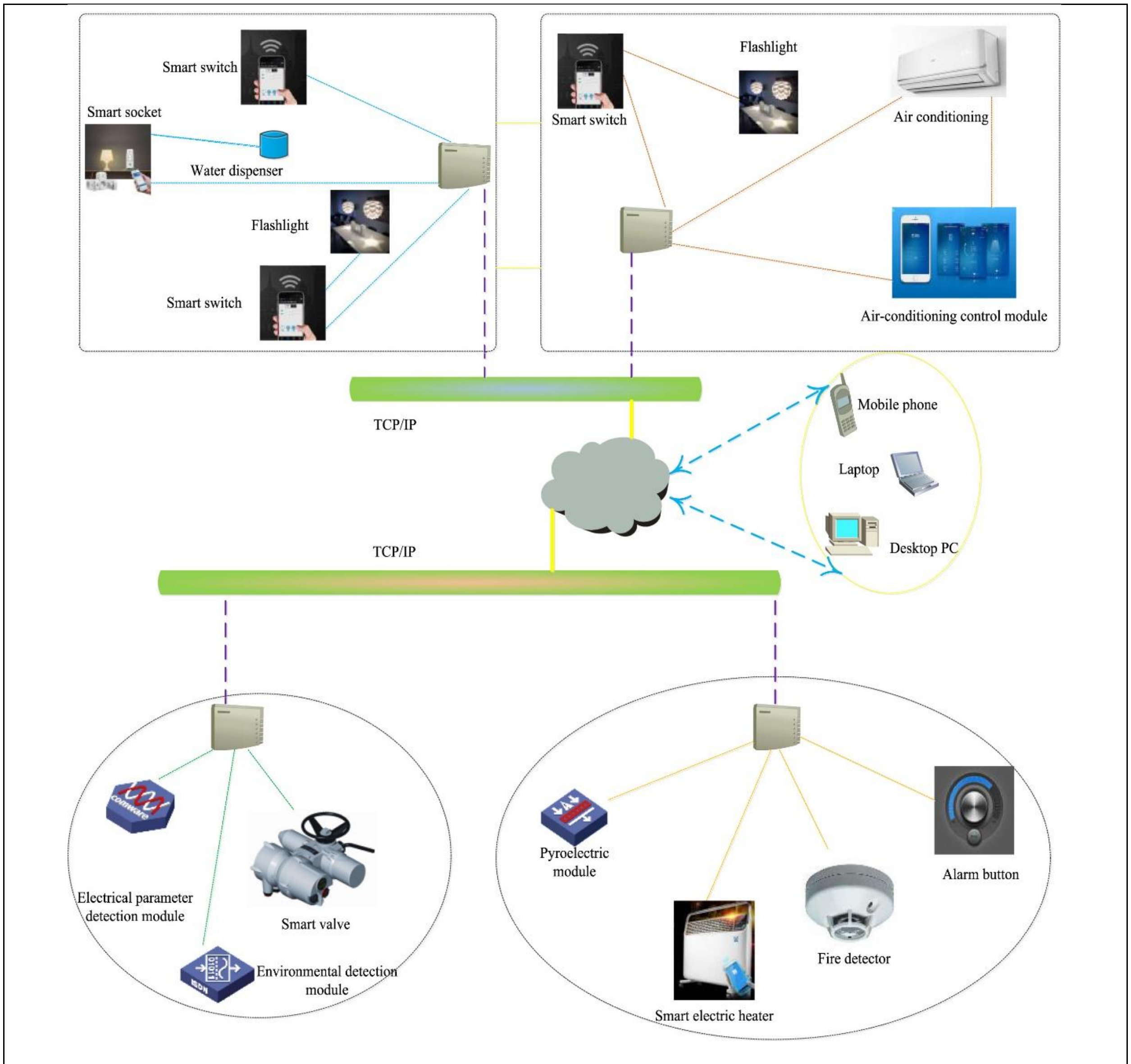

Fig. 3. Indoor electrical IoT architecture (Yu et al., 2020)

Recent industrial infrastructure built on cyber-physical technologies with software linked to the sensors via IoT is called industry 4.0. In smart buildings, equipment and devices can also monitored and regulated to minimize energy usage and enhance occupant’s comfort (Casini, 2014; Pan et al., 2015). IoT technologies have a variety of applications, such as detection systems, communication technologies, cloud technologies and location technologies (Havard et al., 2018). The Internet of Things (IoT) detects and analyzes environmental impacts, such as humidity, temperature, and pressure, to reduce energy consumption in smart buildings (Hossein Motlagh et al., 2020). Smart buildings use IoT sensors to regulate and manage lighting by turning them on and off depending on the zone's occupancy.

Table 3. Framework for assessing the Technology Readiness Level [14]

Technology developer	Application	Scope	Benefits
(Fisher & Hancke, 2014)	Smart Home	Security	Provide security and secure data management
(Tang et al., 2015)	Smart home	Health and wellbeing	Control smart home systems and apps for the elderly and people with disabilities
(Yin et al., 2015)	Smart home	Electricity	Control of electrical loads in smart homes
(Tseng et al., 2014)	Homes	Motion sensing	IoT with motion sensing is utilized in smart homes

5.2. Virtual sensing

Virtual sensing technologies have a huge impact and potential in an informative and reliable sensing environment. It's main function is maintaining intelligent services in building life-cycle and digitalization (Yoon, 2022). Sensing environment is the first phase on building operation, maintenance, automation, and digitalization. Installed sensors for closed control feedback loops of building systems have huge impacts on building energy consumption, operations and control efficiency, also with indoor environmental qualities and comfort (Yoon et al., 2019; R. Zhang & Hong, 2017). Technological advances in the field of micro-electro-mechanical systems, as well as digital electronics, currently hold a large portion of all buildings will be automated and well monitored. Monitored buildings will provide the data through virtual sensors that applied in any building activity such as door locking, energy monitoring, controlling household appliances, etc.

It should be noted that the automation systems have to be connected through network where it can be monitored or controlled, or even used as an actuator to interact with the surrounding environment in which it is embedded. Thus, based on the data provided by the virtual sensors, an automation system can manage the building choosing which are the best scenario that will result in better energy efficiency and comfort to benefit the occupant. This is a growing trend in building automation, especially in developed countries.

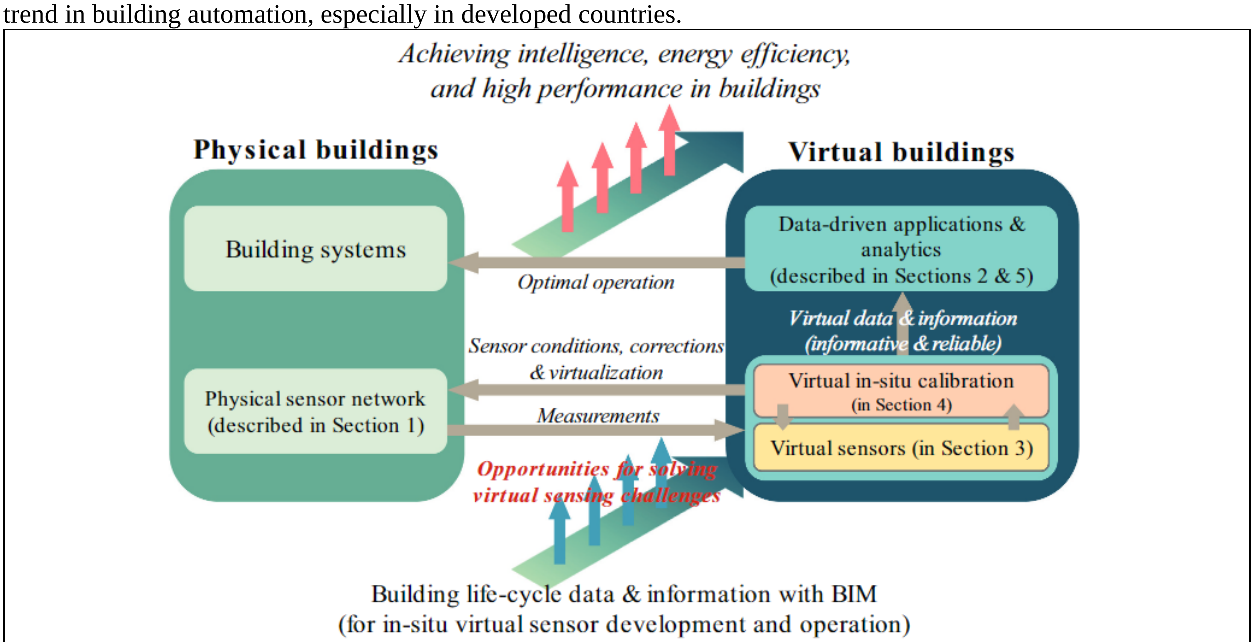

Fig. 4. Diagram of virtual sensing-drive on intelligent buildings (Yoon, 2022).

Virtual sensors are part of simulation models that can provide virtual measurement data from the simulation results. It can help researchers or building modelers substitute physical sensors and measurement systems in the real physical world. Virtual sensors can be coupled with other technologies for better comfort or energy efficiency (Darwazeh et al., 2021; Ploennigs et al., 2011). Edtmayer et al. (Edtmayer et al., 2023) created a novel model-based digital twin of a real physical building and coupled building energy simulation (BES) with computational fluid dynamics (CFD).

Table 4. Virtual sensing application on energy efficiency

Technology developer	Application	Scope	Platform	Benefits
Ploennings et al. (Ploennigs et al., 2011)	Commercial	Room-level heat consumption and thermal comfort	The Environmental Research Institute Building (ERI),	Virtual sensors can optimize building system efficiency and reducing monitoring cost.
Zhao et al. (Zhao et al., 2015)	Commercial	Occupancy sensors for demand-driven HVAC operations	Vertigo Building, Eindhoven University of Technology (Netherlands)	Develop virtual occupancy sensors for applications at public office level and building level.
Revel et al. (Revel et al., 2015)	Residential	Sensors with a control logic using measured data		Provide optimal rules to actuate the controlled devices (window, heating/cooling, etc.)

5.3. Building Information Modelling (BIM)

Building information modelling (BIM) technology is increasingly use in new or retrofitted buildings. The use of BIM in the buildings is not only for monitoring all factors in it, but also related to its energy efficiency. The software can assign non-graphical information to modelled elements, such as materials properties the system and etc. The models created not only used to design the building geometry, but also inserted information that allows different analysis such as energy consumption, estimated cost, structural, daylight, pump system. It is possible for BIM to predict energy performance of the building in conjunction with the thermal comfort for example.

Several studies are carried out in the scope of reducing energy consumption in the buildings using BIM. Fasi et al. (Fasi & Budaiwi, 2015) developed case studies that quantified the energy saving from daylight contribution. Tong et al. (Tong et al., 2016) improved the thermal comfort and maintaining a healthy indoor environment at the same time by reducing the use of cooling with natural ventilation in the building. In addition, thermal environment analysis was performed to produce strategies for the modification of the cooling system as a way to reduce energy consumption (Nazi et al., 2017).

5.4. Digital twin

Digital Twin (DT) was developed to assist product life cycle management through high-fidelity virtual products, also participants are building a complex network through a large amount of product life cycle data (Li et al., 2022). Development of Digital Twins (DT) technology in the construction of sustainable cities can perceive various data information of urban system information in production and provide ecological and environmental protection (Li et al., 2022).

The process may be challenging when the data must be efficiently and securely managed it’s access, authenticity, sharing, and storage (Uhlemann et al., 2017). To solve the problems, Yaqoob et al. use blockchain to reshape and transform DTs in industrial applications that guarantee traceability, compliance, authenticity, quality, and safety (Yaqoob et al., 2020). Lee et al. (Lee et al., 2021) integrate digital twin and blockchain frameworks for information sharing in construction projects.

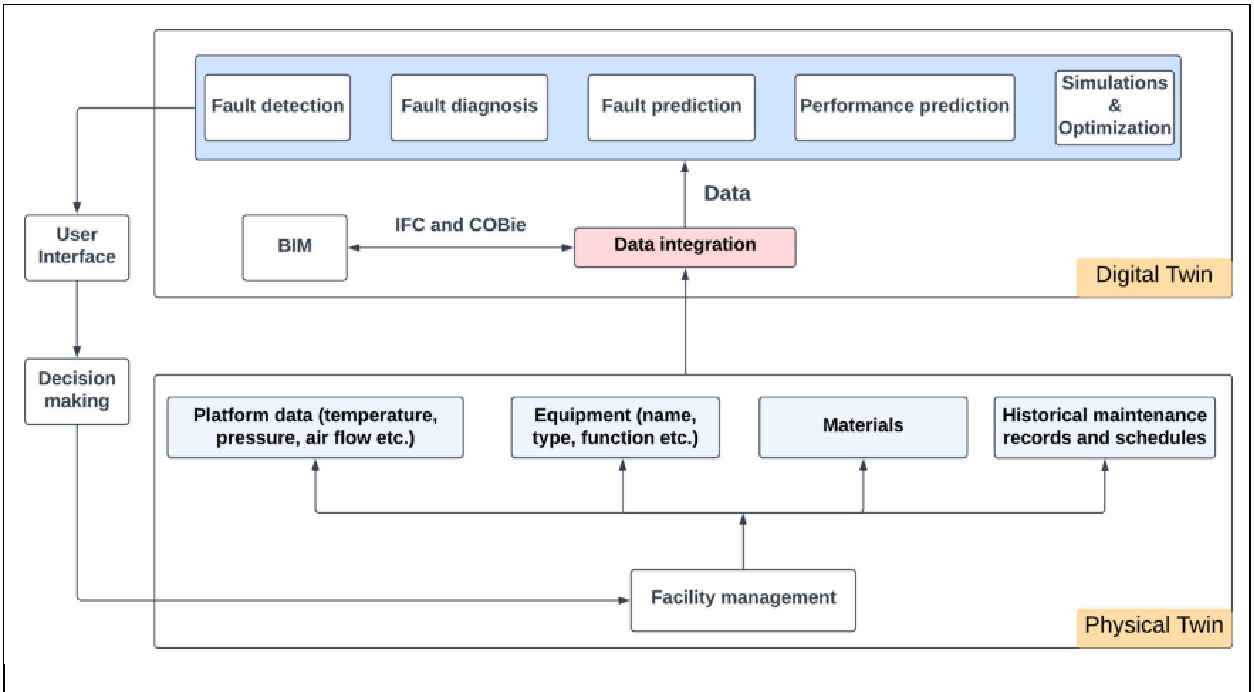

Fig. 5. Digital twin concept for building operation (Hosamo et al., 2023)

Furthermore, DT can be used to improve energy efficiency on operational and maintenance management. Lu et al. (Lu et al., 2020) performed study of anomaly detection on building assets operational condition of heating, ventilation and air-conditioning (HVAC) system as a case study. On the other hand, DT can be integrated with other factors such as comfort, and optimization of the systems that will also reduce energy consumption. Hosamo et al. (Hosamo et al., 2023) developed DT framework for automated fault source detection and prediction for human comfort performance in non-residential buildings. Gnecco et al. (Gnecco et al., 2023) establish a new method for digital twin development for a test room for human comfort and energy behavior analysis through Graph Neural Network. Tan et.al (Tan et al., 2022) combined computer vision and BIM with a DT system on decision-making on lighting control. Collaborative management of lightning system, resulting on reducing energy consumption and electricity costs.

Table 5. Digital Twin Applications for building energy efficiency

Technology developer	Application	Scope	Platform	Benefits
Xu et al. (Xu et al., 2017)	Residential	Data collection and simulation	Residential buildings at the Olympic Central Area in Beijing (China)	Provide model for energy saving.
Jo et al. (Jo et al., 2019)	Commercial building	Simulation model (EnergyPlus, SketchUp)	Commercial pigsty with different fan capacities (South Korea)	Analyze energy performance under several conditions.
Zhang et al. (D. Zhang et al., 2014)	Commercial	Data collection and simulation (eQuest)	Three office buildings in Shanghai (China)	Possibility of reducing energy consumption by different HVAC variations.
Vering et al. (Vering et al., 2019)	HVAC systems	Data collection, odelling (Modelica and Dymola)	HVAC system (ERV unit)	Increase the lifecycle efficiency of HVAC systems.
Lydon et al. (Lydon et al., 2019)	Thermal roof system	Data collection (sensors/smart meters), and simulation (CFD Ansys)	Thermal roof system (hydronic pipework)	Leveraging DT concept in applying thermal roof system on complex buildings roof.

Machado et al. (Machado et al., 2019)	Lightning system	Data collection, modelling (Revit), simulation (BIM-Energy)	Lightning system of research lab of the University of Campina (Brazil)	Create prototype energy consumption monitoring.

5.5. Machine learning and artificial intelligence

Since energy modelling is important for building energy management, studies and research work have been performed to verify and compare various building energy prediction models. Energy data are collected and it will be developed to machine learning (ML) models due to ability to discover statistical patterns. Machine learning provide accurate building energy prediction when the model training process is performed correctly.

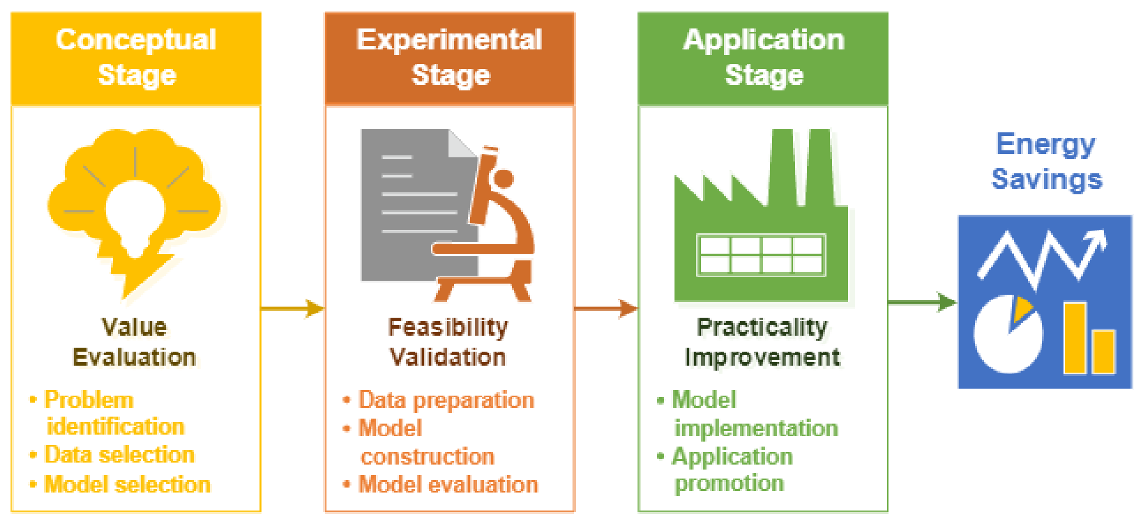

Fig. 6. ML based building energy efficiency implementation process (Wang et al., 2021)

Successful ML technology in building energy efficiency applications requires researcher to follow systematic stages such as conceptual, experimental and application stages as shown in Figure 5. Conceptual stage is targeted to evaluate and analyze the gap or needs and technical feasibility of using ML for building energy efficiency management (Li et al., 2022). This stage requires researcher to have knowledge of building energy management as well as computer science. They have to understand the measures and monitored objects that will result in better energy efficiency and determine the algorithm that matches the developed case.

Next is the experimental stage that seeks to validate predictive performance of ML technology. We need to verify the ability of ML algorithm to fit the available data. This stage consists of two stages: data preparation and model development. Data preparation includes data collection to provide sufficient data , and then processed to improve data quality. Last stage is application stage which seeks to apply the validated ML model, including data composition, ML algorithm and model construction method to an actual building energy efficiency implementation.

Table 6. ML and AI application on energy efficiency

Authors	Application	Scope	Algorithm	Benefits
Chaudhuri et al. (Chaudhuri et al., 2019)	Residential	HVAC	SLF-ANN	Save energy and improve thermal comfort
Zhu et al. (Zhu et al., 2017)	Hotel	Cooling tower, AHU	ANN	Develop an ML model for estimating retrofit project energy-savings.

Sharif et al. (Sharif & Hammad, 2019)	Educational	Building envelope	ANN	Propose an
Yik et al. (Yik et al., 2001)	accurate ANN for energy consumption prediction using data from th SBMO mode			

6. Illustrations

6.1. Digital technologies advantages and disadvantages

Table XX summarizes advantages and disadvantages of digital technologies for energy efficiency described in this section

Table 7. advantages and disadvantages of digital technologies for energy efficiency described in this section

Digital Technology	Advantages	Disadvantages	Example of Available Installations
Internet of Things	Broad usability almost in every aspects of building devices. Cheap and easy to maintenance depends on the systems.	Data security, integration with different sensors.	Smart lamp, smart buildings, CCTV, etc.
Virtual Sensing	Able to simulate every room conditions without physical sensor.	Have to be compared with actual data for accurate measurement.	Occupancy prediction for controlling HVAC. Modelling virtual sensors for indoor comfort control.
Building Information Modelling	Able to provide and process building data. BIM is widely used in newer buildings. Effectively calculate building energy consumption.	Need a lot of investment. Not recommended for residential use.	
Digital Twin	can perceive various data information of urban system information in production and provide ecological and environmental protection	Costly investment. Not recommended for home/residential use.	DT for monitoring maintenance and operating conditions of HVAC.
Machine Learning and Artificial Intelligence	Wide application, can provide decision automatically by the data.	Need to find the effective algorithm for effective use.	Develop an ML model for estimating retrofit project energy-savings.

IoT is the most widely used in residential and commercial buildings among all the digital technologies presented in this study. IoT could be used for building devices automation, monitoring, etc. IoT is cheap and easy to buy in the market, for example, smart lamp or smart meters to control and measure energy used by the devices and can be monitored by phone or computer since it has to be connected to the internet.

In terms of energy efficiency digital technologies that used for specific operations, the digital twin is the most used ones. This is because it is adapting the cases needed for each usage. Most of digital twin technology used in large scale projects, it used big data from multiple sensors to analyze the operational and maintenance data to provide a data-driven platform for realizing an integrated management of the entire life cycle of the projects.

Multiple digital technologies also can be used for the integration of energy efficient modelling to reach the best efficiency for each system. For example, the Digital Twin can be coupled with building information modelling. BIM as a source of the data will be processed by digital twin to improve energy efficiency for intelligent buildings. But it needs big investment to involving the digital technologies to the operation and maintenance in buildings.

6.2. TRL assessment based on survey

Consultant, students, and researcher with different levels of expertise in the applied technology for design and engineering projects are surveyed. The main aim of the surveys was to approach the experts with experience in the digital technology, so the aggregated feedback was expected to be updated in this time. Figure XX presents the experts present occupation. Almost 35% of the respondents are students related to building fields (architectural, mechanical, or civil). The others divided into several work areas such as engineer, architect, researcher, faculty, energy professionals.

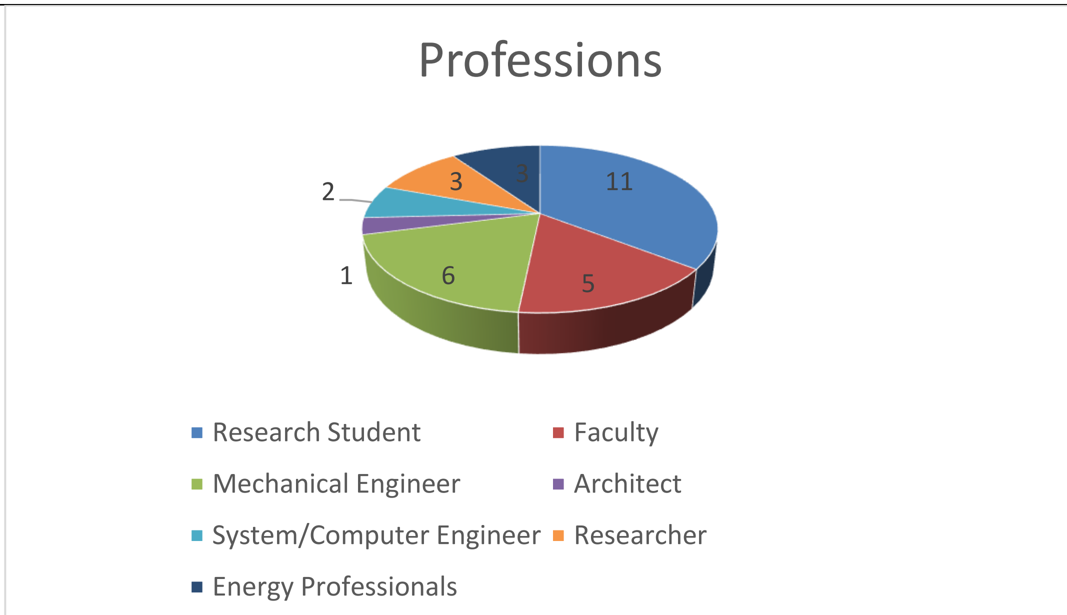

Fig. 7. Specialization of respondents

The experience is varied between 0 year as a research student and more than 10 years. Details of respondents experience are listed below;

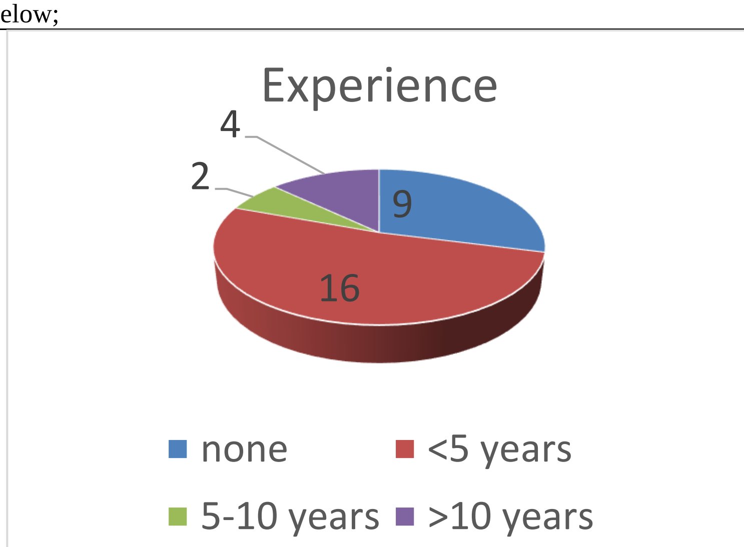

Fig. 8. Respondents experience

Table 8. Key parameters of analysis in technologies for improving energy efficiency

Technologies	Scale of operation	Availability	TRL (Survey)	TRL (Literature Review)
Internet of Things (IoT)	Commercial/residential	Smart cities, smart buildings, utilities, logistics, and industrial.	8	9
Building Management Systems (BMS)	Commercial/Medium to high-rise buildings	Smart cities, smart buildings.	7	9
Building Information Modelling (BIM)	Commercial	Smart buildings	8	9
Smart Meters	Commercial		7	9
Virtual Sensing/Sensors	Commercial		7	9
Digital Twin	Commercial but limited		6	8
Machine Learning	Commercial but limited		7	9
Artificial Intelligence	Commercial		7	9
Blockchain	Commercial		6	8
Occupancy Sensor	Commercial		8	9
Big Data	Commercial		8	9

6.3. Energy saving

The Internet of things in this sector focuses on utilizing low power and consuming less energy in building systems. The development of smart homes and smart cities need IoT to gather data and control appliances (turn off/turn down). We may see IoT in smart cities as parking sensor, waste management or smart lighting, smoke detectors, and alarm systems in smart buildings or homes. IoT can also measure gas, electricity and water use and monitor energy infrastructure. As a basic tools for monitoring the building systems, IoT can present energy efficiency data to the user as a first step of basic understanding on energy efficiency effort. IoT is a broad system from as simple of data collecting and monitoring to analyzing then controlling building systems such as HVAC system. The use of digital twin, machine learning, AI and blockchain in the building energy efficiency sector is growing. In electricity systems, digital technologies can help people to integrate higher shares of variable renewables and better match supply and demand for connected appliances. IEA (International Energy Agency) states that digital technologies can improve efficiency in buildings and transport while enabling a shift to low-carbon options in the end use sectors.

6.4. Technology infrastructure

Digital technologies need infrastructure for it to work properly. The most essential infrastructure on digital technologies is network. Those technologies without network can not be communicate from the sensor to the end user. Each digital technology also needs a server to store, process, and analyze data. Then the collected data will be processed through servers and sent to the end user. The network infrastructure mainly includes the hardware infrastructure related to the information transmission system and software infrastructure such as the network platform and service application which can provide technical support and services for the digitalization (Luo & Yuan, 2023).

Globally, power sector investment in digital technologies rose by around 13% in 2021 to USD 55 billion after a slowdown in 2020, reaching around 18% of total investment in electricity grids. The electricity distribution sector accounts for three quarters of all grid investment in digital, deploying smart meters and automating substations, feeders, lines and transformers via the deployment of sensors and monitoring devices. Enabling digital technologies is essential to fully exploit the flexibility and efficiency potential of the growing number of connected devices. In addition, to ramp up the deployment of key digital technologies, existing data and digital assets must be better utilized to provide more benefits for consumers and the energy system.

6.5. Challenges

Investing on the digitalization, energy efficient and resilient buildings is a cost-effective way to reduce carbon emissions, improving air quality and provide many benefits for the stakeholders. Despite these numerous benefits, the investment opportunities still remain unsecured. Many economies in developing countries such as Asia and Africa are prioritizing other urgent energy policy issues such as energy access, resilient networks, and security of the energy supply. Subsidized energy bills can also be a problem for government since the region faces rising debt levels that can lead to tighter lending conditions. This will make small to medium enterprise or household more difficult and spend more on the investment.

Growing number of digital technologies in buildings or other energy efficiency sectors also face compatibility problems. This problem occurs because of different kind of electronic appliance or systems in each home. Then the home sometimes did not have the minimum requirements to handle such a new cutting edge technologies. Incompatibility of technologies can lead to safety issues, such as fire, or broke down when installing the technologies.

The development of those technologies coupled with the other hardware such as occupancy sensor, HVAC control system, and energy monitoring. For example, blockchain is essential in terms of security reasons. In digital technology, data is critical due to security reasons. Some leakage in data can bring problems to the developed system. Additionally, the tension between human-machine interaction during decision-making could be a problem too. Due to the distrust that the technologies do not match the user perspective or interest, they were often troubled in interpreting and explaining digital data into actionable and human terms. In addition, the adoption of digital technologies in developing economies might be slower since its rapid growth on the development at a very low cost, and some users could not keep pace.

7. Conclusion

This study presented an approach based of measuring TRL on the digital technologies related to building energy efficiency. An expert survey was used to assess the technology readiness level in buildings energy efficiency digital technologies. In terms of opportunity development, individual technologies were analyzed based on technology readiness level assessment in the survey to establish current maturity status and potential development for the future. These technologies reached different TRLs if which IoT, BIM, Occupancy Sensor and Big Data was considered as the most advanced among all listed digital technologies.

This paper also measure the technologies based on its availability on the market. For instance, IoT is already famous and being used in commercial, residential even in the industrial sector for a long time. Some of other technologies are in developing or in the testing phase (Digital Twin and blockchain). These technologies is not available for residential or it just too expensive for home to use these technologies.

This paper contributes to the widening and systematizing of knowledge on the maturity and understanding digital technologies related to energy efficiency. This study hopes to inform researcher, user, and industry to support energy efficiency technology development focusing in the digital technologies.

Acknowledgements

Acknowledgements and Reference heading should be left justified, bold, with the first letter capitalized but have no numbers. Text below continues as normal.

Appendix A. An example appendix

Authors including an appendix section should do so before References section. Multiple appendices should all have headings in the style used above. They will automatically be ordered A, B, C etc.

A.1. Example of a sub-heading within an appendix

There is also the option to include a subheading within the Appendix if you wish.

References

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