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SURVEY OF FLUID POWER APPLICATIONS IN MILITARY MACHINERY

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Abstract. *This work aims to map hydraulic and pneumatic system applications in military machinery and equipment. Hydraulic and pneumatic systems used in the Army are very significant due to their advantages such as the high forces through small devices (high power density) and high response velocity, due to fast-acting with high accelerations, and besides being reliable systems. As a methodology for this work, various databases of scientific papers and research reports were used in order to verify previously developed solutions and monitor the design evolution of mechanisms and fluid power systems used by the Army. As result, a new viewpoint about military machinery centered on three main modular systems is presented including: mechanisms, power drive system, and control system. Highlighting the power drive system, the current state of hydraulic and pneumatic systems is discussed, and it is shown how they are being used in machinery and equipment by the Army.*

Keywords: *military equipment, fluid power systems, machine design*

1. INTRODUCTION

The Army, as well as civil companies, face similar problems such as decreasing budget, increasing capacity, increasing efficiency and a constant concern to be updated to keep up with or stay ahead of the concurrence, but their product development and constraints may be different. Mittal and Caddell (2021) and Harnack (2012) present one important difference which is the product's lifecycle. According to Harnack (2012), military products are commonly designed to last more than 20 years. Many military products use fluid power into their systems to perform their functions. Besides that, fluid power systems also have energy storage capacity through hydropneumatic accumulators, self-lubricating properties, best reliability in hard work, and flexibility of installation of their actuators through a combination of hose and low weight actuators (Durfee *et al*., 2015; Linsingen, 2001).

This paper aims to map hydraulic and pneumatic applications in military machinery and equipment. The mapping was done by systematic research at databases of journals, technical magazines, conferences, and books to classify the use of fluid power in military equipment and machinery. It was done through two approaches, a restrictive approach, which criteria were developed and all of them must be attended, and a comprehensive approach, which some of the criteria of the first approach may not be attended, in other words, military applications may appear instead of military equipment.

The rest of this paper is organized as follows. Section 2 presents the literature review containing fundamental review principles and data collection. Followed by Section 3, which discusses the data found, their results, and their impact. At last, Section 4 presents conclusions.

2. LITERATURE REVIEW

The basis of this literature review is military equipment and fluid power. It is necessary to define each term to find their applications. After defining these terms, the state of the art is presented.

2.1 Military equipment

During this research, many papers and works dealing with military equipment were found in literature, however, a clear difference between military and non-military equipment is not identified. Its lack may impact other definitions. For example, according to Qiang *et al*. (2011), there is not a precise definition of Military Equipment Lean Maintenance. More definitions or a consensus of one definition of military equipment would help to develop the Military Equipment Lean Maintenance definition. All definitions found about military equipment are listed below.

Alexander (1988) describes military equipment, like most other products, as a set of attributes grouped into familiar categories such as performance, cost, reliability, and style. For this type of equipment, reliability has an important role, which must be demanded. Middleton *et al*. (2006) state that "the function of military equipment is to provide tools to allow the armed services to discharge their full spectrum of envisaged activity and to do it well".

On the other hand, the Brazilian Army (Estado-Maior do Exército, 2003) describes Military Employment Material as armament, ammunition, military equipment, and other naval, air, land, and amphibious materials or means for private or characteristic use of the armed forces, as well as their spare parts and accessories. The Brazilian Army (Estado-Maior do Exército, 2003) also describes equipment as all items, except uniforms and armaments, necessary to equip a military or military organization to perform a mission.

Based on the definitions above, the authors of this paper assume that military equipment can be divided into two categories. The first is the equipment of private or characteristic use of the armed forces. For example, armament and ammunition. The second is the equipment (typically non-military) that is being used for military purposes. For example, a vehicle.

Modern military equipment consists of a mechatronic system because it comprises mechanical, electrical/electronic, and information systems and must present high efficiency and accuracy. According to Valdiero and Rasia (2016), mechatronics systems are centered on three main modular systems: mechanisms, power drive system, and control system. The mechanism is a mechanical part that performs the movements of the structure or kinematic chain. The power drive system is responsible for the application of force on prismatic joints or torque on rotating joints in the system. The power drive can be electrical, hydraulic, or pneumatic and it produces a movement of the mechanism. The Control system is the hardware and software part responsible for obtaining and issuing a response signal to start or stop.

The Ministry of Defense works to implement policies and initiatives that seek to improve the operational capacity of the Navy, Army, and Air Force with the search for technological autonomy (Ministry of Defense, 2020). This modernization will increase effectiveness, efficiency, and capacity of the Army machinery and equipment. In consequence of this modernization, the Army will be able to fulfill its missions in the best way possible. This work is intended to show the evolution of equipment and technologies used and to identify where the applications of fluid power systems best suit, besides identifying product ideas and characteristics desirable that have not yet been developed as a way of viewing future products. Within this context, the definition of fluid power systems is presented below.

2.2 Fluid power

Adapting from Linsingen and De Negri (2020), one can define “a fluid power system, from a general perspective, is an arrangement of interconnected components that uses fluid under pressure to provide energy transmission and control”.

Power drive, which uses liquid, like oil or water, is a hydraulic system and when using air it is a pneumatic system. Fluid power circuits feature a conversion of mechanical energy to fluid energy and then convert fluid energy back to mechanical energy (Cundiff and Kocher, 2020). Figure 1 illustrates this concept.

Fluid power applications have many advantages as they can achieve high force and high response velocity. It has a high power density due to its small size. It has an energy storage capacity through hydropneumatic accumulators. The fluid itself has self-cooling properties. Hose and lightweight actuators make its installation flexible. As downside hydraulic fluid needs to be filtered, it can cavitate and cause loss of precision, and fluid power components have some inherent nonlinearities characteristics as friction and leakage.

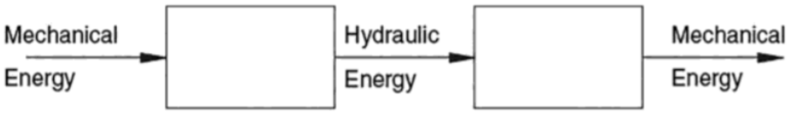

Figure 1. Illustration of the concept of fluid power (adapted from Cundiff and Kocher, 2020)

2.3 Research Methodology

As a methodology for this approach, various databases of scientific papers and reports were used to verify previously developed solutions. As a first approach, focusing on finding recent studies related to military equipment with fluid power systems, criteria presented in Table 1 were used.

Table 1 presents the inclusion criteria. For this approach, an exclusion criterion was also used. If one of the criteria is just cited or used as an example and it is not a part of the subject, then the article found is excluded. In other words, if the work in analyzes loses focus on one of the military, equipment, or fluid power criteria it is excluded. Table 2 presents the results found.

Table 1. Criteria and their explanations.

Criteria	**Explanation**
Military related	The work in analyses must be related to the military area
Related to equipment or machinery	The work in analyses must be related to any sort of equipment or machinery.
Fluid power related	The work in analyses must be related to the application of fluid power

Table 2. Recent research of fluid power.

Application	**Reference**
Armored Engineering Vehicle	Dabing *et al*. (2019)
Artillery	Wei *et al*. (2019) Nie *et al*. (2018)
Exoskeleton robots	Kim *et al*. (2015)
Tank Gun	Zhang *et al*. (2020)
Tracked Armored Vehicles	Guoqiang and Xingye (2014)

Furthermore, a more comprehensive approach was used in order to map military equipment and machinery that uses fluid power. For this research, it is considered Brazilian Army description of Military Employment Material considering private or characteristic use of the armed forces. As a methodology for this approach, databases of scientific papers and reports were used to verify previously developed military solutions. As a result of this research, all criteria of Table 1 may not be attended, but through the references presented it is possible to identify the use of fluid power on those equipment and machinery. The result of this research is presented in Table 3.

Table 3. Applications of fluid power.

Application	**Reference**
Aircraft	Arbuzov *et al*. (2019) Wheeler (2016)
Ammunition Transportation	Yun-long *et al*. (2011)
Explosive Ordnance Disposal	Bartnicki *et al*. (2016) Tran *et al*. (2019)
Exoskeleton	Jha *et al*. (2018) Liang *et al*. (2018)
Missile	Chen *et al*. (2009) Li *et al*. (2008)
Ship	Bruzzese *et al*. (2013)
Simulation Tester	Xu *et al*. (2019)
Tank	Sundaresh (2016)
Unmanned Ground Vehicle	Bartnicki and Klimek (2019) Tran *et al*. (2006)

After the use of the research methodology and review of the papers, the applications of fluid power systems in military equipment were systematized and presented in section 3.1.

3. RESULTS AND DISCUSSION

3.1 Fluid power in military equipment

As a result of the research, Table 4 was consolidated. It presents where some studies from tables 2 and 3 are applied, the purpose why fluid power system is applied, and the hydraulic or pneumatic components that were utilized for the design of the fluid power system circuit.

Table 4. Applications, functionality, and conceptions of fluid power in military equipment.

Application	Functionality	The conception of fluid power system	Reference
Armored vehicle	Reliable positing of an arm (gun, winch) with a linear actuator	A hydraulic system composed of: Double-acting cylinder; 4-way 3-position directional control valve; Pressure relief valve; Bypass valve; Reservoir and Filter.	Dabing *et al.* (2019)
Armored Vehicle	Shifting gear	A pneumatic system composed of: Double-acting cylinder; Single-action cylinder retraction by spring; 5-way 3 position directional control valve; 4-way 2-position directional control valve Proportional pressure control valve; Accumulator; Pressure relief valve; Primary energy conversion unit.	Guoqiang and Xingye (2014)
Self-propelled Artillery	Artillery projectile transfer arm	A hydraulic system composed of: Double-acting cylinder; 4-way 3-position directional control valve.	Wei *et al.* (2019)
Elevation-balancing Machine of Artillery Platform	Precision control of the electro-hydraulic position servo system	A hydraulic system composed of: Double-acting telescopic cylinder; 4-way 3-position directional control valve; Accumulator.	Nie *et al.* (2018)
Exoskeleton Robot	Carry heavy loads	A hydraulic system composed of: Double-acting cylinder; 4-way 3-position directional control valve; 2-way 2-position directional control valve; Hydraulic pump with fixed-displacement; Check valve; Reservoir; Primary energy conversion unit.	Kim *et al.* (2015)
Tank Gun	Rapid response positing	A hydraulic system composed of: Double-acting cylinder; Accumulator; Check valve; Pressure relief valve; 2-way 2-position directional control valve; Primary energy conversion unit; Hydraulic motor Fixed-displacement, two directions of flow, two directions of rotation.	Zhang *et al.* (2020)
Unmanned Ground Vehicles	Increase the working capacity	A hydraulic system composed of: Double-acting cylinder; 4-way 3-position directional control valve; Hydraulic pressure boosters; Accumulator; Hydraulic pump with variable-displacement; Pressure relief valve; Reservoir; Filter; Check valve; Primary energy conversion unit.	Bartnicki and Klimek (2019)
Missile	Improve the robust performance of the system	A hydraulic system composed of: 4-way 3-position directional control valve; Pressure relief valve; Accumulator; Reservoir with drain; Filter; Hydraulic pump with variable-displacement; Primary energy conversion unit; Hydraulic motor with fixed-displacement,	Chen *et al.* (2009)
Missile	Determines the viability and reliability of the armament system.	A hydraulic system composed of: Double-acting telescopic cylinder; 4-way 3-position directional control valve; Pressure relief valve; Reservoir; Hydraulic pump with fixed-displacement.	Li *et al.* (2008)
Ammunition Transport	Simulate vibration test of ammunition transportation	A hydraulic system composed of: Double-acting cylinder; 4-way 3-position directional control valve; Pressure relief valve; Accumulator; Reservoir; Hydraulic pump with fixed-displacement; Primary energy conversion unit.	Yun-long *et al.* (2011)

3.2 State of art

Five military applications of fluid power circuits from Table 4 were chosen to exemplify the current state of the art, how they are applied, and it is also presented some advantages and disadvantages in each case.

3.2.1 Exoskeleton robot

Kim *et al.* (2015) built an exoskeleton robot to increase mobility and the ability to carry heavy loads. The chosen control system was the virtual joint torque control method because it has shown good human-robot interaction. The power drive through hydraulic actuators is used for having a high power density (produces high force with a low weight device), even having a relatively low accuracy and some non-linearity.

Hydraulic systems, represented in Fig. 2, aim to provide high force through a low weight system. This system consists of: an engine, a reservoir, a pump, control valves, temperature sensors, and double-acting cylinders.

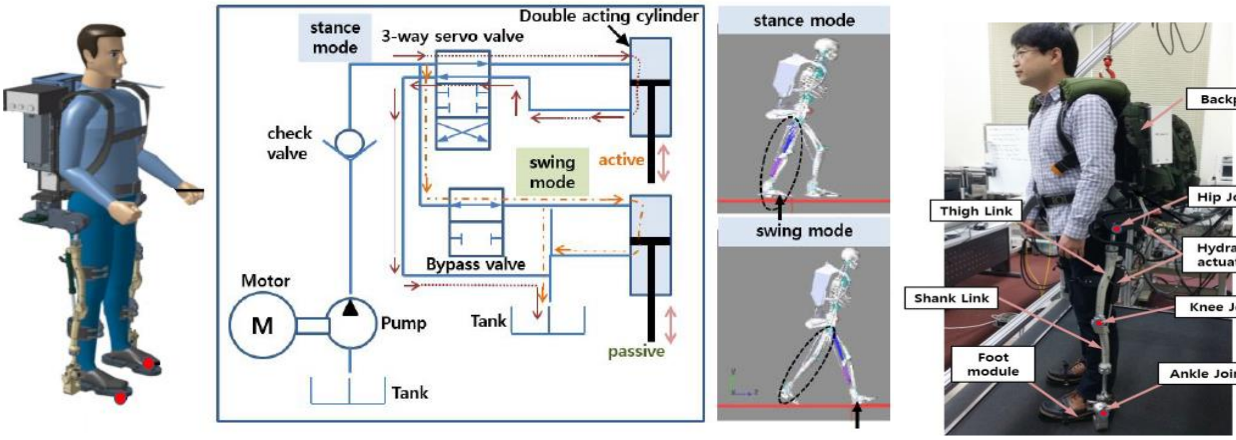

Figure 2. The conception of an exoskeleton robot (adapted from Kim *et al*., 2015)

3.2.2 Missile

Chen et al. (2009) propose an advanced method of active disturbance rejection control (ADRC) to tactical missiles. This method aims to improve the dynamic response and the robust performance of the electro-hydraulic actuator. During the flight, the rudder passes through relevant external disturbances. These disturbances can affect the hinge moment and rudder angle. An electro-hydraulic actuator was chosen because it provides a high driving force with low mass and small volume, fast and continuous response.

The hydraulic system, shown in Fig. 3, is composed of: digital control, current amplifier, directional control valve, pressure relief valves, accumulator, potentiometer, and hydraulic motor. The hydraulic system aims to control the angular position of the rudder.

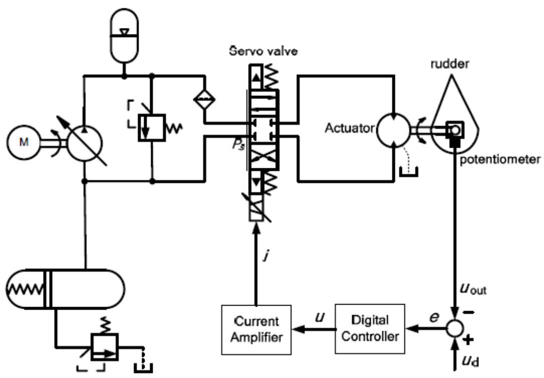

Figure 3. Electro-hydraulic system (source: Chen *et al*., 2009)

3.2.3 **Armored Vehicle**

Guoqiang and Xingye (2014) carried out a refit in the automatic mechanical transmission (ATM) based on the shaft-fixed mechanical transmission gearbox to shift gears rapidly and smoothly. The shaft-fixed mechanical transmission gearbox usually fatigues the drivers because the drivers need to shift gears frequently.

The gear shifting is automated through ATM which requires a control system and a power system. The power system, represented in Fig. 4, is a pneumatic system composed of: gearshift cylinders, directional control valve, pressure relief valve, proportional pressure control valve, accumulators, air compressor, and a single action cylinder with a retraction by spring.

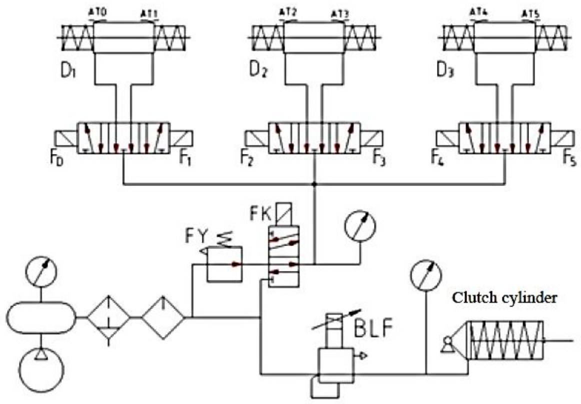

Figure 4. Pneumatic AMT control system (adapted from Guoqiang and Xingye, 2014)

3.2.4 **Tank Gun**

Zhang *et al*. (2020) propose the substitution of the original actuator of a tank gun for a new electro-hydrostatic actuator (EHA) which has a faster response (Fig. 5). The original valve-controlled servo actuator has high control precision and fast response, but it is easily contaminated and has a high cost. The new electro-hydraulic actuator has low energy consumption, low volume, low weight and it is highly reliable. The electro-hydraulic actuator system is composed of: hydraulic cylinder, directional control valve, filter, check valve, pressure relief valve, accumulator, pump, sensor, motor, controller, and driver.

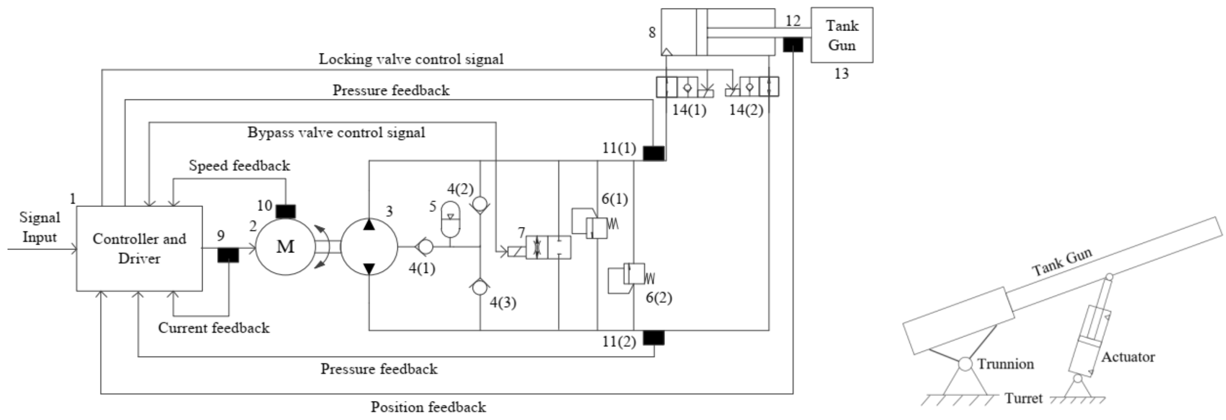

Figure 5. Electro-hydraulic system (adapted from Zhang *et al*., 2020)

3.2.5 **Unmanned Ground Vehicles**

Bartnicki and Klimek (2019) studied the use of a hydraulic amplifier in the drive system of an Unmanned Ground Vehicle. Many Unmanned Ground Vehicles are powered by electricity because it has low consumption of energy which guarantees a greater working time. Since electrical actuators have low power density, a combination of electric and hydraulic drive systems will solve this problem. The resulting system will increase working capacity while using low electric consumption.

The hydraulic system is composed of: an electric motor or fuel motor, pump, check valve, pressure relief valve, directional control valve, pressure intensifier, hydraulic cylinder, sensor, filter, and reservoir.

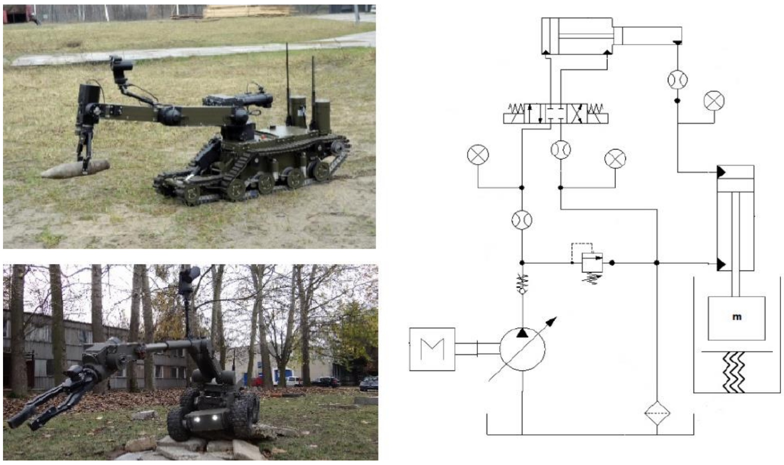

Figure 6. Hydraulic system with pressure amplifier of Unmanned Ground Vehicle (adapted from Bartnicki and Klimek, 2019)

3.3 Data collection

As a result, it was expected to find a greater number of related research for both the approach of military equipment state of art review and for the approach of use of military equipment, presented in section 2.3. This is due to the fact that there are many papers carried out aiming at applications that may not be military.

The restrictions imposed by the criteria of Table 1 may exclude research that may be indirectly related to the objective of this work. The research found may not be directly related to equipment, machinery, or military application, but it can be indirectly applied in this type of equipment. Either through direct application or as part of an equipment subsystem. This can be seen from the point of view of the use of off-the-shelf products as defense equipment (Mathopo and Marnewick, 2017) and from the point of view of Harnarck (2012) who says that the use of off-the-shelf products with shorter life cycles are often used as components.

A similar interpretation can also be obtained by remarking the function of military equipment stated by Middleton *et al*. (2006). When non-military equipment fulfills the function requirements of military equipment, that non-military equipment can be used as military equipment. As an example, a pneumatic muscle for robotic manipulators (Robinson *et al*., 2015) can have applications in the military area.

Another explanation for fewer paper publications of state of art regarding military equipment is that information may be classified information. Information security is important for many groups as industry, government, and academia (Schumacher and Ghosh, 1999).

3.4 Data analysis

Through the data obtained from tables 2 and 3 and the point of view of the use of off-the-shelf products, it is possible to notice that the use of fluid power applications is very comprehensive. Due to the wide application of non-military system solutions in military equipment, the evolution of such equipment and technology will follow non-military technologies. Taking this into account, it can be noticed that equipment that does not use fluid power can benefit from it. For example, ammunition can indirectly benefit from the ammunition transport study by Yun-long *et al*. (2011).

From Table 4 it can be seen that there is a wide variety of fluid power applications with different functionalities. This is a consequence of the variety of fluid power circuits. These conceptions, either hydraulic or pneumatic, can be improved in two different ways: firstly, using the same circuit with better and more efficient components. For example, the use of Digital Hydraulic Actuator (Belan, 2018) or Electro-Hydrostatic System (Agostini *et al*., 2020) in substitution of the Electro-Hydraulic Actuator. Secondly, through designs with different circuits that provide greater efficiency or work capacity to the equipment. The best application of fluid power depends on the scenario that it is applied due to their constraints inherited.

Regarding the military equipment evolution, it was noticed that they are turning into mechatronic systems to improve their accuracy, response, and effectiveness. The military equipment, which already is mechatronic systems, is evolving by improving its parts either being mechanism, power drive, or system control. For example, Guoqiang and Xingye (2014) carried out a refit on a tracked armored vehicle to improve the shifting gear. Another example is the study of Bartnicki and Klimek (2019) developing a hybrid electric and hydraulic system to provide higher force with lower consumption of energy.

A mechatronic equipment system can be divided into 3 parts (mechanism, power drive system, and control system). Even with the improvement of the control system or mechanism a power drive will still be necessary to produce the force or to generate the movement. This shows the importance of power drive and fluid power.

4. CONCLUSION

It was not found a clear definition of the difference between military and non-military equipment, as it depends on the purpose for which the equipment is being used. Based on other definitions, the authors present a new point of view of military equipment.

Even though military equipment does not directly utilize fluid power technology, there are several indirect ways in which it benefits from it. Therefore, it can be concluded that the application of fluid power is increasing as the equipment becomes mechatronic systems to increase efficiency, accuracy, or capacity. Therefore, there are opportunities for engineering improvement using more efficient technologies.

The results of this work can also serve as a guideline for future research and improvement of military equipment and machinery considering new aspects of energy efficiency.

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