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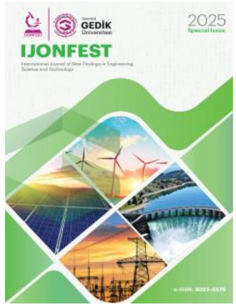


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# Reference Energy System Analysis of a Main Battle Tank

Uğur Leblebici[a*], Egemen Sulukan[b], Bülent Ekici[c]

[a] *Marmara Üniversitesi, Makine Mühendisliği Bölümü, 34722 İstanbul, Türkiye, ugurleblebici@marun.edu.tr (*Corresponding Author)*
[b] *Istanbul Gedik Üniversitesi, Makine Mühendisliği Bölümü, 34876 İstanbul, Türkiye, egemen.sulukan@gedik.edu.tr*
[c] *Marmara Üniversitesi, Makine Mühendisliği Bölümü, 34722 İstanbul, Türkiye, bulent.ekici@marmara.edu.tr*

**Abstract**

Energy plays an indispensable and vital role in daily life today. This role has compelled countries to share global energy resources and lead to wars throughout human history. Especially after the Industrial Revolution the intensive use of fossil fuels has led to an increase in greenhouse gases and caused climate change. Massive carbon emissions have necessitated a comprehensive effort to reduce carbon emissions. As in many other fields, numerous initiatives have been undertaken in the military field to address this issue. United Nations, NATO and European Defence Agency are undertaking various efforts to implement measures aimed at reducing carbon emissions while preserving the operational capabilities of militaries. Using energy modeling tools for energy planning is one of these efforts. In military field, main battle tanks (MBT) are among the most carbon-intensive military vehicles due to their high fuel consumption. In this study, an energy network for a Leopard 2A4 main battle tank was created and components were specified within a flowchart based on the concept of a reference energy system. On this basis, it will be possible to define and analyze the subunits of the established reference energy system using real data in the LEAP energy decision support tool. Furthermore, it is aimed to provide ideas for innovations that can reduce carbon emissions while preserving the operational effectiveness of main battle tanks.

***Keywords:*** Reference Energy System, Main Battle Tank Energy Analysis, Energy Modeling, Energy Efficiency.

## 1. INTRODUCTION

A Main Battle Tank (MBT) is an armored, fully tracked combat vehicle designed to engage stationary and moving enemy targets with long-range and high firepower, capable of operating in various weather conditions both day and night [1]. MBT is equipped with weapon and fire control systems capable of visually identifying and engaging targets. The tank crew uses these systems to locate and classify the target, select the appropriate weapon and ammunition based on the type of target, measure the target's distance, and execute the shot. Main battle tanks gain superiority on the battlefield against the enemy thanks to their maneuverability, firepower, and survivability provided by their thick armor.

The Leopard 2A4 tank is a main battle tank in the medium tank class, equipped with a 120 mm gun, featuring optical stabilization and an independent periscope for the tank commander, with superior survivability due to its composite armor structure [2]. It can be used effectively against armored targets with its smoothbore tank gun and against ground and air targets with its machine guns. Thanks to its thermal vision system, the Leopard tank has effective target detection and identification capabilities during day, night, poor visibility conditions, and against camouflaged targets. Its pressurized CBRN (Chemical, Biological, Radiological and Nuclear) protective equipment enables safe operation in contaminated or radioactive field without endangering the crew. With additional equipment, it can pass through water obstacles up to 4 meters deep.

The most important characteristic of the main battle tank is its ability to demonstrate military dominance on the battlefield and remain operational even under the most difficult conditions. Therefore, it must not only be resistant to any possible military threat but also remain in constant readiness even in the harshest environmental conditions [3]. Military decarbonization efforts are crucial for climate change. Oil Change International estimated that the U.S. military emitted 100 million metric tonnes of $CO_2$ in fuelling its war in Iraq in five years [4]. The U.S. Department of Defense is the largest industrial consumer of fossil fuels in the world. DoD consumed about 117 million barrels of oil in 2011 [5].

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As in many other fields, certain institutions and organizations worldwide are conducting studies in the military sector on reducing greenhouse gas emissions, ensuring energy security, and energy modeling such as United Nations, NATO, European Defence Agency and the International Military Council on Climate and Security. International Military Council on Climate and Security (IMCCS) examines the challenges and opportunities presented by climate change for global militaries. It explores how innovation, particularly in low-carbon technologies, can address the dual challenges of climate adaptation and emissions reduction while maintaining operational readiness [6]. Also, it evaluates how military innovation can play a critical role in reducing climate risks and adapting to new challenges, emphasizing the importance of international cooperation and public-private partnerships.

NATO has a special department for conducting research about energy security called ENSEC COE (Energy Security Center of Excellence). NATO and Partner for Peace (PfP) countries recognize energy security as vital to overall security. Innovative EE and RE solutions, like hybrid systems and renewable energy installations, are crucial to reducing environmental impact and operational risks [7]. So, NATO propose integration of energy efficiency (EE) and renewable energy (RE) solutions in military operations, emphasizing sustainability and innovation in energy management. NATO's efforts for energy security are conducted under various themes such as technological innovations for operational efficiency, strategic goals and challenges, civil-military cooperation, and country-specific initiatives. To improve sustainability, integration of solar panels, hybrid power systems, energy storage are proposed solutions. Mobile solar power plants, hybrid electric vehicles, wearable batteries, and smart grids are technological innovations to reduce greenhouse gas emissions in military. Besides, scientists from the U.S. Army Combat Capability Development Command Ground Vehicle Systems Center (GVSC) and U.S. Army Research Laboratory continue developing new hydrogen combat vehicles, includes tanks and infantry fighting vehicle [8].

## 2. THE SIGNIFICANCE OF MAIN BATTLE TANK ENERGY SYSTEM ANALYSIS

Main battle tanks are known for their high energy inefficiency, toxic properties and disproportionate contributions to climate change. For example: M1 Abrams tank gets 0.2 miles per gallon (compare this with a fuel-efficient car like the Toyota Prius that gets 51 mpg.) [9]. Since many main battle tanks still rely on conventional fossil fuels, implementing energy optimization and modeling their energy system will enable us to reduce greenhouse gases and contribute to decrease the effects of climate change. Tanks rely heavily on fossil fuels because they provide the high energy density required for long operational ranges and durability in extreme conditions. The energy density of current alternatives like batteries or hydrogen is not yet sufficient to replace diesel fuel without sacrificing performance. But efforts are conducted as the U.S. Army Research Laboratory continue developing new hydrogen combat vehicles, including tanks [10]. Increasing the efficiency and modernization of main battle tanks in a more cost-effective, high-performance and environmentally friendly manner will not only contribute to national economies but also represent a significant step in the fight against climate change. Conducting an energy system analysis of a main battle tank to ensure that it operates more efficiently and with reduced carbon emissions are just as important as preserving and enhancing its operational effectiveness.

Significant scientific studies have been conducted to enhance the energy efficiency of main battle tanks and reduce their carbon emissions. C.O. Ilie et al. propose an electric transmission system for the Romanian TR-85M1 tank to increase mobility, efficiency, and battlefield survivability in the study called “Aspects of Electric Transmission Implementation on a Battle Tank.” In order to transform the TR85M1 tank into an armored hybrid combat vehicle, an energy system consisting of a diesel engine, gas turbine, electric transmission with AC generator, two traction motors and electronic power module is proposed [11]. In his study “Hybrid-Electric Drive Concept for High Speed Tracked Vehicles”, Ilijevski analyzed a hybrid-electric propulsion system for main battle tanks (MBTs) that integrates mechanical and electrical technologies to improve the efficiency of conventional hydraulic transmissions. It is emphasized in the study that not only old-style hydraulic transmissions consume large amounts of energy, but they also require a cooling system that consumes almost 15% of the power generated by the engine to dissipate heat. To address this inefficiency, modeling and kinematic calculations of a hybrid electric drive system were carried out, showing that the electric motor integrated system enhances efficiency and saves fuel [12]. In the study entitled “Design Aspects of an Electric Propulsion System for Brazilian Army Leopard Vehicles with Fuel Cells”, Felix Alberto Farret et al. evaluated the feasibility of converting the Brazilian Army's Leopard 1A5 tanks to hydrogen fuel cell electric vehicle (FCEV) propulsion. In this study, the replacement of the Leopard 1A5's MTU MB 838 diesel engine with an electric motor powered by hydrogen fuel cells is investigated. The authors argue that this integration could increase vehicle efficiency to around 90%, a significant increase compared to the 20% efficiency typically achieved by internal combustion engines [13].

Leopard tank energy system analysis and integration of technological innovations will contribute all counted combat abilities directly or indirectly. Hybrid or electric-powered tanks may offer operational advantages, such as reduced thermal and sound signatures, improving stealth. Energy efficiency in a main battle tank helps in optimizing fuel consumption, enhancing operational range, and minimizing the need for frequent refueling in battle. A well-designed energy system ensures that all various systems (such as turret movement, weapons systems, and onboard electronics) that require significant power components operate seamlessly, allowing the tank to engage targets effectively without power failures. Tank operations often require high energy use for various functions (weapons, communications, etc.). Optimizing the energy system can help reduce logistical burden, such as fuel supply chains, and improve overall operational effectiveness.

## 3. REFERENCE ENERGY SYSTEM CONCEPT

The Reference Energy System (RES) is a representative network that shows energy transitions and transformations from sources to demand technologies that meet demands. It is a set of parameters that define the characteristics of technologies and resources, such as fixed and variable costs, technology availability, performance and pollutant emissions [14].

It is a flowchart which includes energy carriers, resources, technologies and demands of a system. In a system, it is helpful to summarize and show relationships among various parameters using a network diagram referred to as Reference Energy System. Fig. 1 gives a simplified representation of a typical RES showing the five main components usually recognized in each model structure: primary energy sources (SRC), energy conversion technologies (CON), other energy processing (PRC) and energy end uses (DMD), and the demands (DM) for energy services and energy products [15].

## 4. IMPLEMENTATION OF RES CONCEPT ON MAIN BATTLE TANK

A main battle tank analysis model, including the whole energy input, satisfied demands, demand technologies and relevant conversion and process technologies have been determined and classified in terms of energy system analysis basis, from reference energy system (RES) point of view. In this flowchart, the horizontal and vertical relationships between resources, technologies and energy carriers are shown. A generalized RES of a main battle tank is shown on Fig. 2. Proposed RES consists of six main columns.

In this horizontal flow chart, energy follows a journey from resources to demand technologies. In this journey, energy stored at the resource or imported energy is transformed into other forms of energy. This transformation process is enabled by the elements listed in the “Conversion and Process Technologies” column.

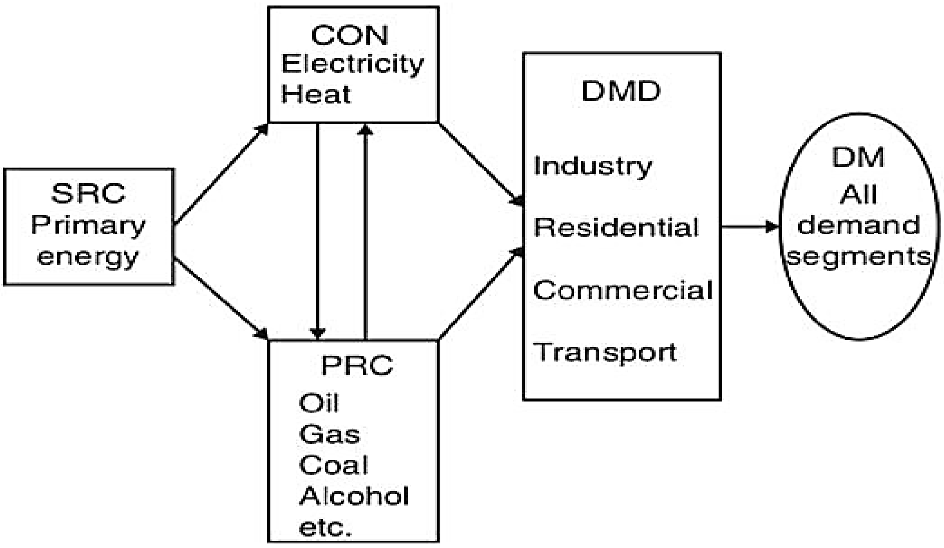


**Figure 1.** Simplified representation of a typical RES [15].

### *4.1 Resources*

A main battle tank has different types of resources which are classified in the RES and shown on Fig. 2. Diesel fuel is the main energy source for a main battle tank. In this tank, F-54 and lubricating oil are used as fuel types. Batteries are converting stored chemical energy into electrical energy and provide electricity for system while main engine is not running. And as electricity resource, eight batteries are used. Every two batteries are connected in series, and four groups are connected in parallel. The battery capacity of the main circuit supplying the body electricity is 300 amperes, consisting of 3 parallel groups, with each group containing 2 batteries connected in series. The battery capacity of the sensitive circuit supplying the turret electronics, consisting of one group of batteries, is 100 amperes. The operating voltage of a battery is 24 volts when the engine is off and 28 volts when the engine is running.

### *4.2 Primary Energy Carriers*

Energy resources enter the main battle tank's energy system as F-54 diesel, lubricating oil and electricity which is shown in figure 2. Electricity resource is obtained from stored chemical energy in batteries. The batteries supply electricity to the system when the engine is not running. When the engine is running, the system electricity is supplied by the alternator and the batteries are charged at the same time.

### *4.3 Conversion and Process Technologies*

Conversion and process technologies refer to specific types of technologies or processes within the energy system that transform energy from one form to another or produce useful outputs like electricity, heat, or fuels. In RES, five conversion and process technologies are defined as shown in figure 2 are as follows: Main engine, transmission, starter engine, battery and alternator. Triggering electricity is produced by battery's stored chemical energy and it is used by starter engine to start main engine. After the main engine starts, it powers the alternator with its kinetic energy. From this point on, the main electricity of the tank is produced by the alternator to feed all electricity consuming subsystems of tank. Alternator also charges battery simultaneously while it is producing electricity from main engine's rotation.

### *4.4 Final Energy Carriers*

Final energy carriers are specified as electricity and heat in a main battle tank as shown in Fig. 2. The heat energy obtained from the main engine and transmission ensures the operation of the elements providing the main propulsion. As the final energy carrier, electricity, is generated by the alternator at 28 volts when the main engine is running and supplies the entire system. When the engine is not running, the system electricity is supplied by the batteries at 24 volts. Alternator's current is converted to direct current by rectifiers.

### *4.5 Demand Technologies and Demands*

Demand technologies are those devices that are used to satisfy end-user service demands directly [16]. 63 demand technologies are defined for 8 demands as shown in Fig. 2. Demand technologies and corresponding demands in a main battle tank are shown in Table 1.

**Table 1.** Demand technologies and demand of a main battle tank.

| Demand Technologies | Demands |
|---|---|
| Tension Wheels | MOTION AND MAIN DRIVE SYSTEM |
| Support Rollers | |
| Torsion Shaft | |
| Direction Rolls | |
| Drive Sprockets | |
| Hydraulic and Mech. Shock Absorber | |
| Tracks | |
| Brake System | |
| Gear Reducers | |
| Fuel Supply Pump | |
| Injectors and Injector Pump | |
| Fuel Filters | |
| Pre-Heating System | COOLING |
| Cooling Fans | |
| Mechanical Coolant Pump | |
| Heat Exchangers | |
| Electric Water Pump | |
| Main Headlights | LIGHTING |
| Masked Headlights | |
| Side Marker Lights | |
| Reflectors | |
| Stop and Brake Lights | |
| Convoy Tracking Light | |
| Ceiling Lights | |
| Map Lights | |
| Signal and Dimming Lights | |
| Electric Water Pump | HEATING |
| Turret Heater and Fan | |
| Driver Heater and Fan | |
| Radios | COMMUNICATION |
| Radio Command Boxes and Headsets | |
| Fans | VENTILATION |

| Demand Technologies | Demands |
|---|---|
| 120 MM Tank Gun | OPERATION |
| Turret Machine Gun | |
| Smoke Mortars | |
| Gunner and Commander Turret Handle | |
| Gun Cyro | |
| Turret Cyro | |
| Computing Electronic Unit | |
| Sensors | |
| Crew Command Boxes | |
| RPP 1-8 Test Device | |
| RPP 1-8 Test Device Elc. Unit | |
| Fire Control Computer | |
| EMES-15 Rangefinder | |
| Laser Electronic Unit | |
| Thermal Vision Devie | |
| TVD Electronic Unit | |
| PERI-R17 | |
| PERI-R17 Electronic Unit | OPERATION |
| FERO-Z18 Scope | |
| Hydraulic Power Unit | |
| WNA-H22 Turret Electronic Unit | |
| 120 MM Tank Gun | |
| Main Contact Emergency Switch | SECURITY |
| Emergency Button | |
| Relay Box | |
| Main Warning Lamp | |
| Fire Alarm Light | |
| Command Boxes | |
| Control Lamp | |
| Coarse Dust Fan | |
| Main Fans | |
| Internal Tank High Pressure Gauge | |

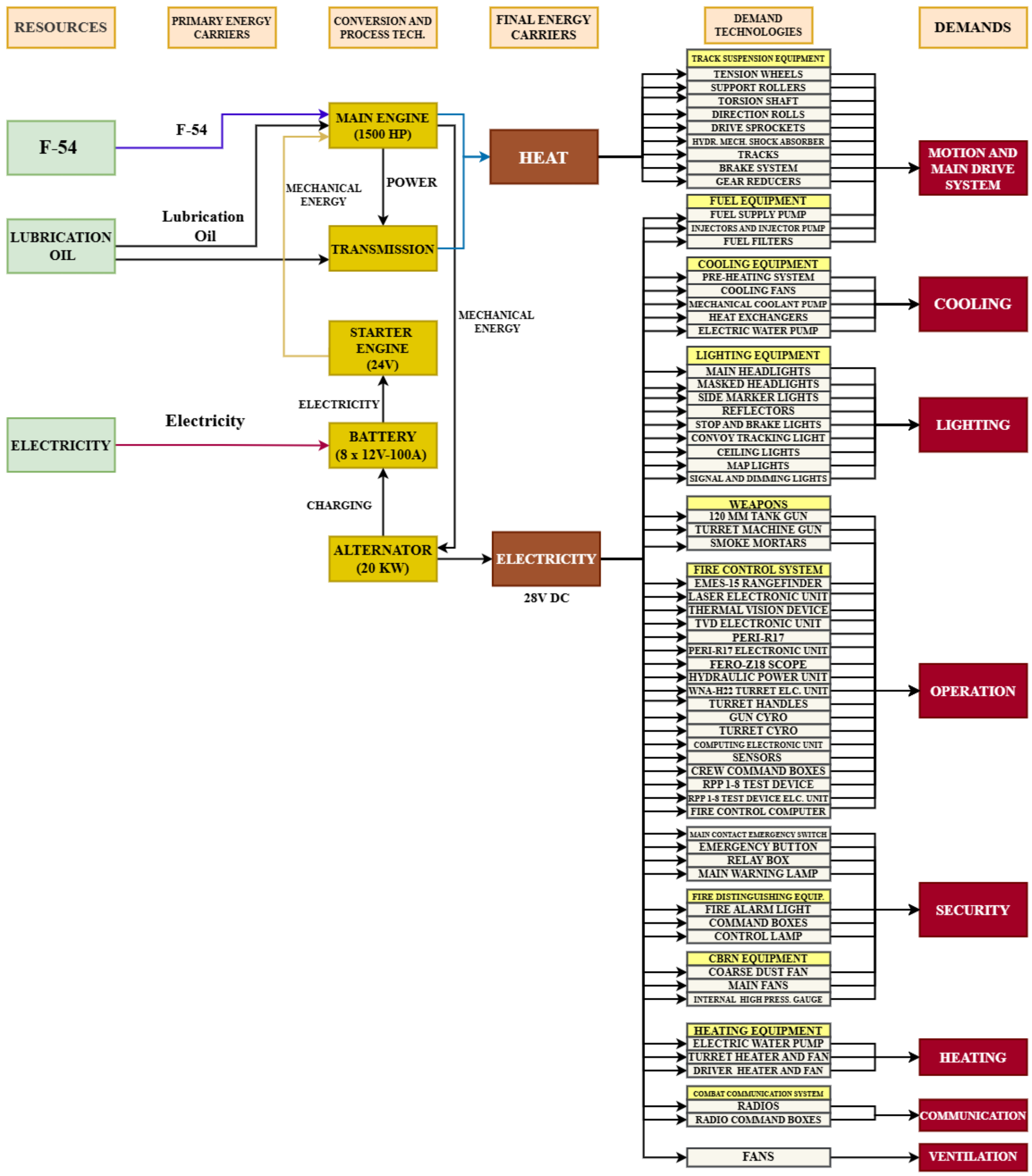


**Figure 2.** Reference energy system of a main battle tank.

## 5. CONCLUSION

In this paper, a comprehensive energy system analysis has been conducted for a German-made Leopard main battle tank profile. The main battle tank energy system analysis model, including all energy inputs, satisfied demands, and relevant technologies, has been determined and classified in terms of the energy system analysis basis, from the reference energy system point of view. By evaluating the real current and voltage data obtained from the technologies within the main battle tank's energy system along with their usage durations, the energy consumption of the main battle tank will be determined in the LEAP. This energy consumption data will be the main issue to be optimized to reduce carbon emission in tank. As output, the energy balance and findings related to the system will be analyzed for the Leopard main battle tank. In following studies and at the conclusion of the research, the goal is to define and analyze the subunits of the established reference energy system using real data obtained from measurements and technical manuals in LEAP energy decision support tool. These data will serve as inputs for the LEAP and will form the basis of the analysis. The current reference energy system and initial data will be considered as the baseline scenario and compared with the analysis results. Additionally, findings and recommendations will be presented regarding the factors that can reduce the carbon emissions of a main battle tank. Ultimately, the goal is to provide ideas for innovations that can reduce carbon emissions while preserving the operational effectiveness of main battle tanks which are still prevalently used in armies.

## Authors' Contributions

| No | Full Name | ORCID ID | Author’s Contribution |
|---|---|---|---|
| 1 | Uğur Leblebici | 0009-0001-7737-8031 | 1,2,3,4 |
| 2 | Egemen Sulukan | 0000-0003-1138-2465 | 1,2,3,4 |
| 3 | Bülent Ekici | 0000-0001-8967-0649 | 1,2,3,4 |
| 1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing | | | |

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