Analysis of Different Engine Types in Aircrafts with Exergetic Approach

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Abstract: The main purpose of exergy analysis is to determine the maximum possible work that can be obtained and to decrease inefficiencies on the system. Exergy analysis provides information about the intensity and positions of inefficiencies. In literature, there are studies for different purposes, types of engines and aircraft, both civil and military. In this work, many different studies were taken as basis. A total of five different types of turbofan, turboprop and turboshaft engines have been analyzed in terms of energy and exergy. First, information has been given about selected engines, technical specifications and usage areas. Next, general thermodynamic analyses and their details are presented. In this context, general and thermodynamic working principles of the aircraft engines have been identified. Then, these identifications have been extended for each of the engines and the thermodynamic analyses as well. Indications are shared with the help of general assumptions. In the final section, results of all studies and data are presented.

Keywords: Aircraft, exergy analysis, turbofan engine, turboprop engine, turboshaft engine, exergy efficiency, inefficiency.

1.INTRODUCTION

Airline transportation is crucial to become a global market in consequence of economic developments. Especially as the demands on speed, safety and comfort increase, transportation systems also show the same improvement; thus, both countries and companies have increased their investments in these directions. Since Turkey has an important geographic position, passenger numbers increased from 34 million in 2003, to 193,3 million in 2007 in total [1- 3].

Globally, energy consumption and efficient use of energy sources is of great importance. The main purpose of studies in this direction can be generalized as ensuring correct usage of resources, sustainability and decreasing costs [7].

When examined thermodynamically, thermal systems have to obey both the First Law of Thermodynamics (energy conservation) and the Second Law of Thermodynamics (exergy analysis, utility). analysis, utility). The First Law of Thermodynamics is also named as "law of energy, the energy conservation" and this law clarifies the balance between the work that system applies to its environment and heat rate that is accrued to the system. Energy analysis is concerned with the system quantity and does not take into account losses when irreversibility happens. The Second Law of Thermodynamics gives the information of entropy production during the state changes of the system, decrease of energy quality, and utilization of the capability of work in system. While some of the exergy in the system is disappearing because of the irreversibilities, others are dumped to the environment from system's boundaries [8].

By the transformation of actively used types of energy such as wind, electricity and aircraft engines, different forms of both sustainability and providence are achieved. Especially aircraft engines are studied thermodynamically, revealing new progress due to their capacity of high-rate energy productivity. Aircraft engines are commonly classified into three main categories as turbofan, turboprop and turboshaft [7].

Turbofan engines, which are also known as “fanjet”, are the combination of fans and turbines. The biggest difference of fanjets from turboprop engines is the by-pass ratio, which is also known as the “air flow ratio”. Turbofans are divided into two sub-categories as “low by-pass ratio” and “high by-pass ratio”. Low by-pass ratio turbofan engines are preferred in civil aircraft due to their performance in long haul flights by producing high thrust, low volume and their compact bodies.

Turboprop engines are not capable of producing a high rate of energy; so, most of the produced energy is used to rotate propellers. In contrast of turbofan engines, turboprop engines are more productive in low speeds.

Turboshaft engines are the types of engines which show properties like high power output, high reliability, small body-size and light body-weight. In general; turboshaft and turboprop engines have common working principles. The difference between turboprops and turboshafts is the mechanic part that transfers energy [4].

2.THEORETICAL ANALYSIS

Before making thermodynamic analysis of a system, defining thermodynamic terms in the system and their main components are important and beneficial for further study.

Total exergy amount in a system is equal to summation of physical, chemical, kinetic and potential exergies [2- 9].

$$\varepsilon = \varepsilon_{kn} + \varepsilon_{pt} + \varepsilon_{ph} + \varepsilon_{ch} \tag{1}$$

$$\varepsilon_{kn} = \frac{V^2}{2} \quad \left(\frac{m}{s}\right)^2 \left(\frac{1kJ/kg}{1000m^2/s^2}\right) \tag{2}$$

$$\varepsilon_{pt} = gz \quad \left(\frac{m}{s^2}\right)(m)\left(\frac{1kJ/kg}{1000m^2/s^2}\right) \tag{3}$$

$$\varepsilon_{ph} = \left[(h - h_o) - T_o(s - s_o)\right] \tag{4}$$

$$\bar{\varepsilon}_{ch} = -\bar{R}T_o \sum x_k \ln \frac{x_{o,k}}{x_k} \tag{5}$$

$$\bar{\varepsilon}_{ch} = \sum x_k \bar{\varepsilon}_{ch,k} + \bar{R}T_o \sum x_k \ln x_k \tag{6}$$

Total energy amount in a system is equal to summation of physical, chemical, kinetic and potential energies, just like exergy [2- 11].

$$e = e_{kn} + e_{pt} + e_{ph} + e_{ch} \tag{7}$$

$$e_{pt} = gz \quad \left(\frac{m}{s^2}\right)(m)\left(\frac{1kJ/kg}{1000m^2/s^2}\right) \tag{8}$$

$$e_{ph} = u + Pv = c_{P(T)}T = h_{(T)} \tag{9}$$

$$e_{kn} = \frac{V^2}{2} \quad \left(\frac{m}{s}\right)^2 \left(\frac{1kJ/kg}{1000m^2/s^2}\right) \tag{10}$$

$$e_{ch} = H_a + h_{(T)} = H_a + c_{P,F,i}T_i - c_{P,F,o}T_o \tag{11}$$

$$e_{ch} = H_u + h_{(T)} = H_u + c_{P,F,i}T_i - c_{P,F,o}T_o \tag{12}$$

With the help of above equations, derivations for components of aircraft engines can also be carried out. The schematic description of low by-pass rate JT8D turbofan engine and some typical terms are explained below mathematically [11]. Calculation of main components of AE3007H engine were done as well, but now shown in this paper.

General exergy balance equation [11];

$$\sum \dot{E}x_{t,in} = \sum \dot{E}x_{u,out} + \sum \dot{E}x_{w,out} + \sum \dot{E}x_{dest,out} \tag{13}$$

where $Ex_{t.in}$ is the chemical exergy of fuel that is burned in the combustor, $Ex_{u,out}$ is the useful exergy output, $Ex_{w,out}$ is the waste exergy output and $Ex_{dest,out}$ is the output of exergy destruction.

Waste exergy equation is as follows [11];

$$\dot{E}x_{w,out}^{JT8D} = \dot{E}x_{t,in}^{JT8D} - \dot{E}x_{u,out}^{JT8D} - \dot{E}x_{dest}^{JT8D} \tag{14}$$

where $Ex_{w,out}$ is the waste exergy output of JT8D, $Ex_{t,in}$ is the chemical exergy of fuel in JT8D, $Ex_{u,out}$ is the useful exergy of JT8D and Ex_{dest} is the exergy destruction of JT8D.

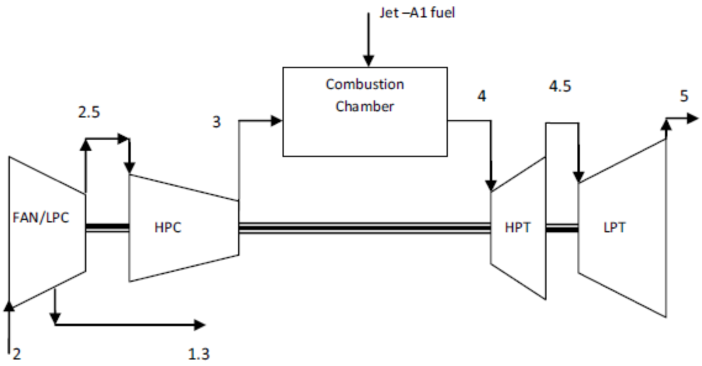

Figure 1. Schematic view of JT8D turbofan engine main components [7]

Exergy efficiency of JT8D is [11];

$$\eta_{ex}^{JT8D} = \frac{\dot{E}x_{u,out}^{JT8D}}{\dot{E}x_{t,in}^{JT8D}} \tag{15}$$

Waste exergy ratio is equal to the ratio of total waste exergy output to total inlet exergy [11];

$$r_{we} = \frac{\sum \dot{E}x_{w,out}}{\sum \dot{E}x_{in}} \tag{16}$$

Identification of T56 turboprop engine system and thermodynamic terms are listed below:

Energy balance equation in control volume and steady-state condition is [6];

$$\dot{Q} - \dot{W} + \sum_{in} \dot{E}_{in} - \sum_{out} \dot{E}_{out} = 0 \tag{17}$$

where Q is the net amount of energy transfer by heat, W is the net amount of energy transfer by work and E is the net amount of energy that in and out.

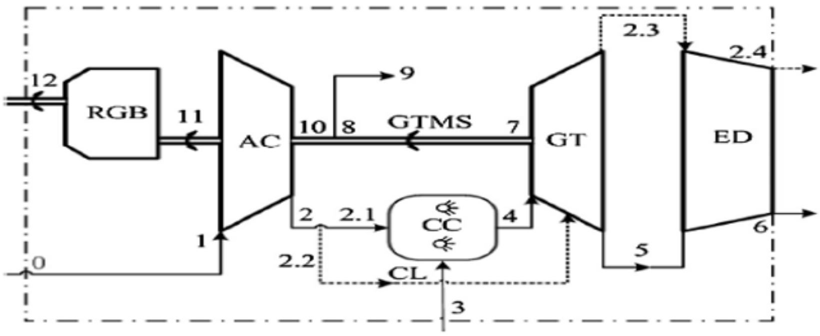

Figure 2. Schematic view of T56 turboprop engine [7]

For better explanation, some terms are identified on the basis of main components below:

For combustion chamber (CC) [11];

$$\dot{m}_{in} \cdot c_{P,a,in} T_{in} + \eta_{CC} \dot{m}_f \cdot LHV = \dot{m}_g c_{P,g} T_{out} \tag{18}$$

$$\dot{m}_{in} + \dot{m}_f = \dot{m}_g \tag{19}$$

where $c_{p,g}$, $\dot{m}_f$, $\dot{m}_g$, LHV and η_{CC} are specific heat capacity of combustion gases, mass flow of fuel, mass flow of combustion gases, the low heating value of the fuel and the combustion energy efficiency, respectively.

For exhaust dust [6];

$$\dot{Q}_{out} = \eta_{ED} \dot{Q}_{in} \tag{20}$$

For gas turbine mechanic shaft (GTMS) [6];

$$\dot{W}_{AC} + \dot{W}_{RGB,in} = (\eta_{GTMS}\dot{W}_{GT} - \dot{W}_{Acc}) \tag{21}$$

For reduction gearbox (RGB) [6];

$$\dot{W}_{Pr,TPE} = \eta_{RGB}\dot{W}_{RGB,in} \tag{22}$$

T56 turboprop engine was compared with PT6 turboprop engine, but the data is not given in this paper [7].

Makila 1A1 turboshaft engine identification with scheme and both general and component based thermodynamic descriptions are listed below. The turboshaft could not be compared with other turboshaft engines due to inadequate data in the literature. It is compared with other general engine studies.

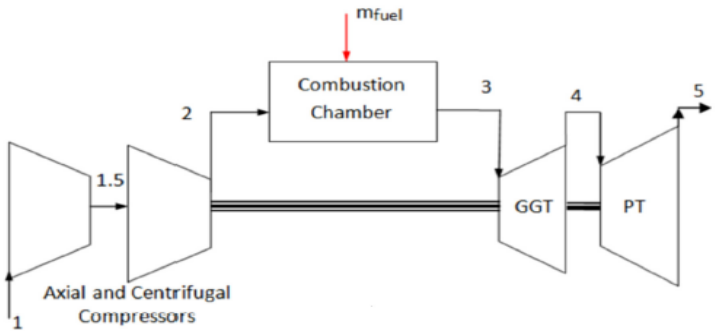

Figure 3. Schematic view of Makila1A1 turboshaft engine [7]

Enthalpy equation in steady state [6];

$$\nabla\cdot(\rho\hat{\delta}h_i\mathbf{V}) = \nabla\cdot\left(\bar{\bar{\tau}}\mathbf{V}\right) - \nabla\cdot\mathbf{q} \tag{23}$$

Mass balance equation [2- 6];

$$\sum \dot{m}_i = \sum \dot{m}_o, \tag{24}$$

General energy balance is described as sum of income and outcome energy equivalencies [2-9];

$$\sum \dot{E}_i = \sum \dot{E}_o \tag{25}$$

General exergy balance [2- 9];

$$\eta_{ex} = \frac{\dot{E}x_i}{\dot{E}x_o} = 1 - \frac{\dot{E}x_{dest} + \dot{E}x_{loss}}{\dot{E}x_i} \tag{26}$$

where η_{ex} is equal to addition of exergy destruction and exergy loss divided by exergy inputs.

While the formulations above are applied for main engine components, some inferences are given below:

For centrifugal compressor (C_eC) [6];

$$\sum \dot{E}x_{in,CeC} - \sum \dot{E}x_{out,CeC} = \sum \dot{E}x_{dest,CeC} \tag{27}$$

$$\sum \dot{E}x_{in,CeC} - \sum \dot{E}x_{out,CeC} = \dot{W}_{CeC} + \dot{E}x_{1.5} - \dot{E}x_2 \tag{28}$$

$$\dot{W}_{CeC} = \dot{m}_a(h_2 - h_{1.5}) \tag{29}$$

$$\eta_{ex,CeC} = \frac{\dot{E}x_2 - \dot{E}x_{1.5}}{\dot{W}_{CeC}} \tag{30}$$

For axial compressor (A_xC) [3];

$$\sum \dot{E}x_{in,AxC} - \sum \dot{E}x_{out,AxC} = \sum \dot{E}x_{dest,AxC} \tag{31}$$

$$\sum \dot{E}x_{in,AxC} - \sum \dot{E}x_{out,AxC} = \dot{W}_{AxC} + \dot{E}x_1 - \dot{E}x_{1.5} \tag{32}$$

$$\dot{W}_{AxC} = \dot{m}_a(h_{1.5} - h_1) \tag{33}$$

$$\eta_{ex,AxC} = \frac{\dot{E}x_{1.5} - \dot{E}x_1}{\dot{W}_{AxC}} \tag{34}$$

For combustion chamber (CC) [3];

$$\sum \dot{E}x_{in,CC} - \sum \dot{E}x_{out,CC} = \sum \dot{E}x_{dest,CC} \tag{35}$$

$$\sum \dot{E}x_{in,CC} - \sum \dot{E}x_{out,CC} = \dot{E}x_2 + \dot{E}x_{fuel} - \dot{E}x_3 \tag{36}$$

$$\eta_{ex,CC} = \frac{\dot{E}x_3}{\dot{E}x_2 + \dot{E}x_{fuel}} \tag{37}$$

For power turbine (PT) [3];

$$\sum \dot{E}x_{in,PT} - \sum \dot{E}x_{out,PT} = \sum \dot{E}x_{dest,PT} \tag{38}$$

$$\sum \dot{E}x_{in,PT} - \sum \dot{E}x_{out,PT} = \dot{E}x_4 - \left(\dot{W}_{PT} + \dot{E}x_5\right) \tag{39}$$

$$\eta_{ex,PT} = \frac{\dot{W}_{PT}}{\dot{E}x_4 - \dot{E}x_5} \tag{40}$$

For gas-generator turbine (GGT) [3];

$$\sum \dot{E}x_{in,GGT} - \sum \dot{E}x_{out,GGT} = \sum \dot{E}x_{dest,GGT} \tag{41}$$

$$\sum \dot{E}x_{in,GGT} - \sum \dot{E}x_{out,GGT} = \dot{E}x_3 - \left(\dot{W}_{GGT} + \dot{E}x_4\right) \tag{42}$$

$$\dot{W}_{GGT} = \eta_m \cdot \left(\dot{W}_{AxC} + \dot{W}_{CeC}\right) \tag{43}$$

$$\eta_{ex,GGT} = \frac{\dot{W}_{GGT}}{\dot{E}x_3 - \dot{E}x_4} \tag{44}$$

3.RESULTS

In this paper, some energetic and exergetic parameters of selected engines have been examined. Each of the engine parameters are compared with their counterparts at different conditions by using calculations and identifications listed above. While considering each parameter, calculations are also applied to make comparisons between AE3007H and JT8D turbofan engine, T56 and PT6 turboprop engine (not all of the studied data is shown in this paper). However; Makila1A1 comparisons could not be completed due to absence of parameters in literature.

Figure 4 demonstrates the exergy efficiencies of turbofan engines. As seen above; the highest efficiency at different conditions is seen in high power turbine (HPT), whereas the lowest efficiency is seen in both of the engines combustion chamber (CC).

On the other hand, exergy destructions in both of the turbofan engines are seen in combustion chamber (CC) respectively. On the contrary; the lowest exergy destruction is seen in high power turbine (HPT). Combustion reaction totally affects the exergy destruction due to chemical reactions.

Figure 5 (left) illustrates exergy efficiencies of studied turboprop engines. Like turbofans, the most efficient component is gas turbine; in contrast to the least efficient combustion chamber. Combustion reaction directly affects whole efficiencies, this means that more reaction means less efficiency. Another figure (right) describes exergy destructions of turboprop engines. As expected, highest destruction is seen in combustion chamber while gas turbine has the least.

In Figure 6; Makila1A1 turboshaft engine exergy efficiency values are shown for main components. Like others, the most efficient component is gas generator turbine (GGT), compared to the least efficient component the combustion chamber. On the contrary; destruction of exergy is observed for the turboshaft engine. The results are the same for other engines.

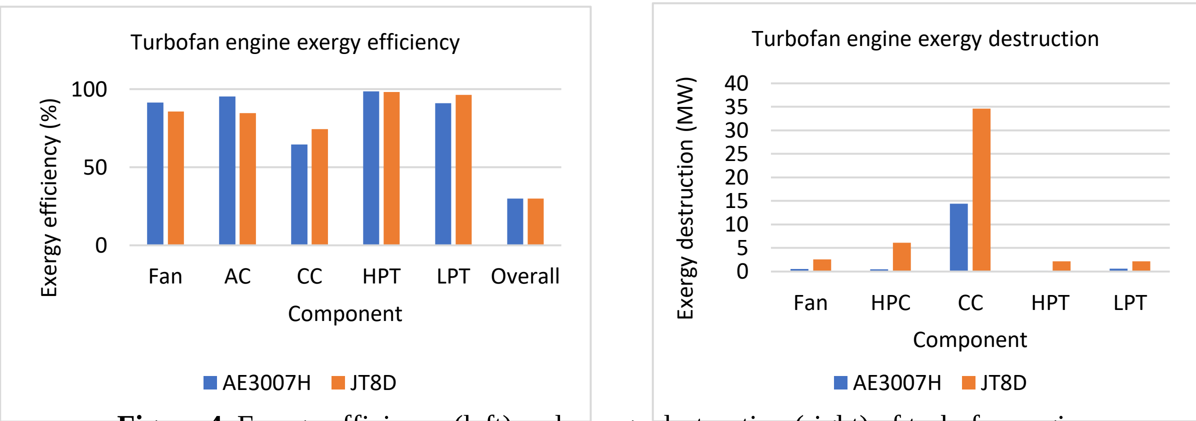

Figure 4. Exergy efficiency (left) and exergy destruction (right) of turbofan engine

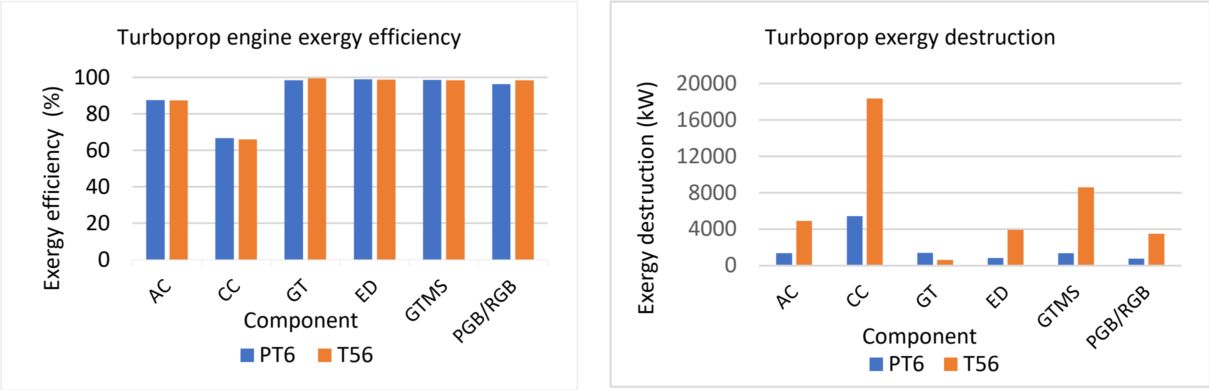

Figure 5. Exergy efficiency (left) and exergy destruction (right) of turboprop engine

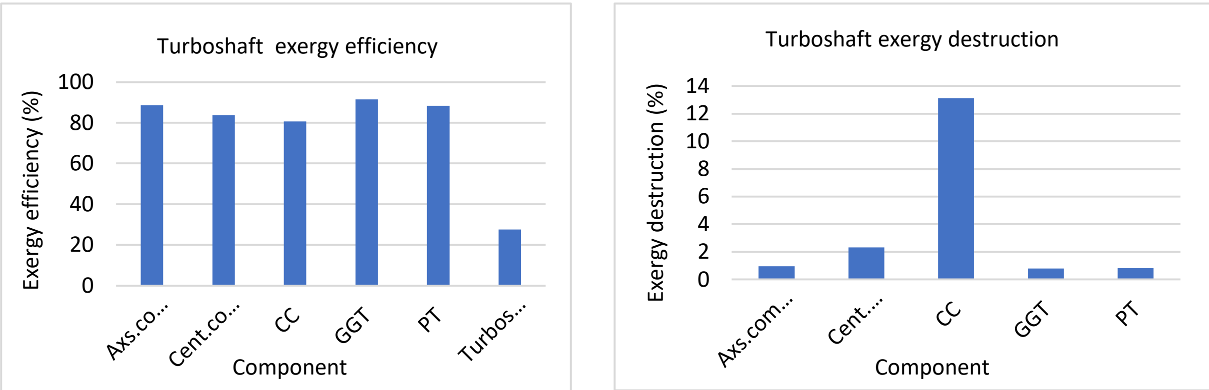

Figure 6. Exergy efficiency (left) and exergy destruction (right) of turboshaft engine

4.DISCUSSION

During the study of analysed aircraft engines; some assumptions and simplifications are applied to make analyses shorter and finding results easier. These assumptions are given below:

- All of the studied engines are assumed as steady-state during operation time. Flow of air and other combustion gases in engines are assumed to behave ideally, and the combustion reaction is complete.
- Engine accessories are not included during these analyses. The potential and kinetic exergies are neglected, because their effect for total is nearly zero. The fuels in engines are assumed to burn ideally; their chemical formulas are taken as $C_{11}H_{21}$ for JetA1 and $C_{12}H_{24}$ for JP-8. All of the components in engines are assumed adiabatic while heat loss is accepted as zero.
- Ambient temperature and pressure of JT8D are 288,15 K and 101,35 kPa same as AE3007H. For T56; these values are 298,15 K and 93,6 kPa, same as PT6. For Makila1A1, values are 288 K and 101,3 kPa, respectively.

When a comparison is made between all engines, the highest exergy destruction occurs in the combustion chamber. That result can be decreased via some design change; but never decreased to nearly zero. The reason for this is the irreversibility of combustion reaction. On contrary; exergy destruction is lower in fan, compressors and turbines. According to Ref (7), it is possible to proceed with alternative methods for these components.

Engine exergetic performance is also linked with environmental factors. For instance;

exergy efficiency increases in higher altitudes, and decreases in lower altitudes. Therefore, the lowest exergy efficiency is observed in take-off, climb and landing phases of flight.

To increase shaft power in the engine; fuel flowrate should be raised. To increase fuel flowrate also increases shaft power, so exergy efficiency is observed in higher degrees.

Whether from common consideration or advanced exergetic analysis results, it is clearly realised that the combustion chamber, air compressor and power turbine are more dominant than other components. These are also identified as key components to achieve better R&D results among engine components that were investigated above. Also, sustainability and exergo-economic studies lead to better results in terms of efficiency.

5.CONCLUSION

In this paper; some parameters of selected engines (AE3007H, JT8D, T56, PT6, Makila1A1) at different conditions have been investigated. These parameters have been compared with each one and in general.

During the study, engines are operated in different environmental or working conditions and compared with each other, so that similarities and differences linked to the conditions can be better observed.

In summary, even if considered at different cases and conditions; all the energetic-exergetic balances and their effects on engines are in total agreement with the first and second law of thermodynamics. This can be understood from performances of engine components during operation.

Engine manufacturers and developers are still following new inventions to develop more advanced engine components, so that better efficiency can be achieved in future.

Environmental effects (pollution, adverse effects on nature or human etc.) must not be forgotten during all studies. Common aim for all studies must be “more efficient engines for environmental benefits”.

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