

Power plant selection in a carbon constrained world the TERA (technoeconomic environmental risk analysis)

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Abstract: There is an increasing concern that current trends of consumption of natural resources cannot continue. It is imperative that major targeted investments are made into economical and reliable environment friendly propulsion and power solutions. Many novel and promising concepts are being proposed. The selection of the best candidates to pursue for investment becomes a very difficult choice.

A detailed TERA (technoeconomic environmental risk analysis) framework is described here to quantify risks and to compare and rank competing schemes on a formal and consistent basis. This technique is based on detailed and rigorous thermodynamic representations of power plants. A layer of environment, economic, weather and other models to describe the appropriate local conditions is superimposed to this.

The outcome is a technoeconomic environmental risk analysis framework with appropriate detail of each power plant as applied to the appropriate conditions. The results for each concept can then be compared and contrasted to make appropriate selections.

Key words: TERA (technoeconomic environmental risk analysis); technoeconomic; risk analysis; gas turbine; multi disciplinary optimisation (MDO)

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Introduction: novel power and propulsion systems

There is much and justified concern about the impact of human activities on the environment. Anthropogenic pollutants have reached very high levels. As a result a large variety of promising power and propulsion concepts are being proposed to mitigate or eliminate CO₂ and other emissions. Among them are new aircraft engines with conventional and novel cycles, nuclear power plants, carbon capture schemes, renewable energy sources, including onshore and offshore wind and wave energy systems, plus many others.

A common feature of many of these systems is a large balance of plant around the PCU (power conversion unit). The systems envisaged are larger and more complex than the state of the art today. Inevitably this will result in an increase in the first cost of the plant, an increased challenge in reliability and availability and more complex operating procedures. Furthermore the combined objectives of economic and environmental performance make the decision process much more difficult. These challenges will need to be addressed when evaluating investment performance.

In addition, for many of these concepts there is little or no relevant operating experi-

ence. So the selection of the best candidates in which to invest scarce research and development funds is difficult and uncertain. The risks are high. Furthermore the impact of local conditions will have a large influence on the economic and environmental performance of the power plants.

A detailed TERA (technoeconomic environmental risk analysis) is described. This method increases the visibility of the risks and enables the user to compare and rank competing schemes on a formal and consistent basis.

Cranfield University has conceived and is deploying such techniques within the European power and propulsion context. The core of the TERA consists of detailed plant and component mathematical models. These models can be coupled with environment, economic and risk models. They can be used to deliver a reasonably clear view of the relative risks and benefits of promising but uncertain concepts. The objective of the TERA is to rank and select the best schemes and identify risk so that investment resources can be allocated efficiently.

The results of a TERA exercise can thus inform investors, legislators and other stakeholders of the best investments needed to achieve a cleaner environment and hopefully accelerate the accrual of benefits from advanced low carbon power and propulsion systems. This method offers an independent and consistent evaluation procedure to allow comparative studies of complex systems encompassing to local and global conditions. It allows interested parties to evaluate policy across countries through local and global conditions to show the competitive advantage of nations.

1 The origins of the TERA

The Cranfield team focusing on power and propulsion has had a key interest in gas turbine performance models for a very long time. For example work on complex energy and power systems was carried out within a variety of contexts and for different customers. This included work on aero-derivative power generation plant^[1], use

of coal synthetic gas^[2-4], work on degradation and diagnostics^[5-6], carbon mitigation studies^[7-8], nuclear gas turbines^[9] and other topics.

Much work carried out for industrial customers has not been published. This list includes research on novel bottoming cycles, advanced hydrogen fuel cycles for power generation, further nuclear gas turbine work, fog injection, many types of aircraft engines, turbomachinery for renewable energy sources, a novel piston engine system and others.

This interest is coupled with work and experience on environmental issues and economic performance, given that these are key selection criteria. It was then natural, over the years, to develop modelling techniques that encompassed combined thermodynamic, economic and environmental algorithms. These gave rise to a very interesting method, the TERA.

2 Description of the TERA

Cranfield is leading the development of the TERA for many applications. Within the European Union context, the TERA for civil aviation is being deployed, with the support of several leading European Universities, for the projects VITAL, NEWAC and DREAM. These focus on advanced environment friendly civil aircraft gas turbines and partners include major aircraft manufacturers, makers of gas turbines and propulsion systems plus research establishments, component suppliers and universities.

A version of the TERA has been produced for the marine sector within a project embracing another two British leading universities. TERA methods are being developed for power generation and the oil and gas industry in association with two major players in the energy field, a power generation company and an oil company. Combined elements of some of these, and other associated work, are described here to give a flavour of the TERA and the range of current applications.

3 The power plant and the duty

The core of the TERA framework requires a

detailed thermodynamic description of the power plant capable of giving the off design and, sometimes, the degraded performance of the engine. For these purposes, Cranfield University has deployed TURBOMATCH (the Cranfield University, in-house, legacy gas turbine performance simulation software).

In the case of a vehicle (aircraft or ship), a mathematical model of the vehicle is necessary. Consequently Cranfield University have developed an aircraft model (HERMES) and a ship model (POSEIDON).

The case study described below is related to a marine TERA framework application and is based on the ship analysis described in Ref. [10]. The propeller data, the ship’s anatomy and the engine design point data are summarised in Table 1, Table 2 and Table 3 respectively.

Table 1 Propeller data [10]

Parameters	Data
Propeller diameter (D_p/m)	5.1
Pitch diameter ratio (P/D_p)	1.154
Expanded area ratio (A_E/A_0)	0.763
Propeller rotational speed ($N_{prop}/(r/min)$)	150
Number of blades (N_{blade})	5
Open water efficiency (η_{bp})	0.695

Table 2 Ship anatomy [10]

Parameters	Data
Length at water level (L_{wl}/m)	185.55
Maximum beam (B/m)	25.0
Average design draft (T/m)	6.4
Block coefficient (C_b)	0.55
Mid ship coefficient (C_m)	0.93
Water plane coefficient (C_{wp})	0.69
Service speed ($V_s/knots$)	29.0
Froude number (Fn)	0.3469
Displacement ($S/tonnes$)	17000
Wetted surface (S_w/m^2)	4950

Table 3 Engine design point data [10]

Parameters	Data
Gas turbine rating ($P_{PT}/(\times 2/MW)$)	25
Turbine entry temperature (TET/K)	1500
Compressor pressure ratio (PR_c)	17.8
Intake mass flow ($W_i/(kg/s)$)	68
Exhaust mass flow ($W_e/(kg/s)$)	69.5
Exhaust gas temperature (T_{exh}/K)	829
Thermal efficiency (η_{th})	0.374
Specific fuel consumption ($SFC/(g/kWh)$)	224
Specific power ($c_p/(MJ/kg)$)	0.367

Additionally, an input of the time domain of the mission is required. This can be a description of the flight details (mission profile) of an aircraft, the journey of a ship, the daily duty of a power station and others. In the case of the marine application, a comparison of a journey in the following three different scenarios was examined:

- S1: Calm sea and “clean” ship
- S2: Stormy sea and “clean” ship
- S3: Stormy sea and fouled hull

The engine rating was based on hot section temperature. The outcomes of the three scenarios are illustrated in Fig. 1 and Fig. 2.

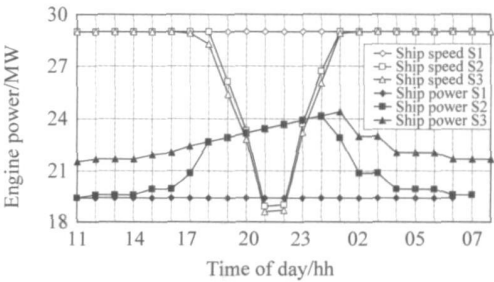


Fig. 1 Engine power and ship speed characteristic

Fig. 1 shows, for S1 (the calm sea with “clean” hull scenario) a departure in the middle of the morning and a journey, where the ship travels at a constant speed and the power required from the power plant is always the same. For this scenario, Fig. 2 shows the change of turbine entry temperature needed to offset the effect of changing ambient temperature during

the journey. The fuel flow is also shown. There are some small variations in fuel flow, not discernible in the graph, due to the small changes in thermal efficiency arising from the change of power setting of the engine.

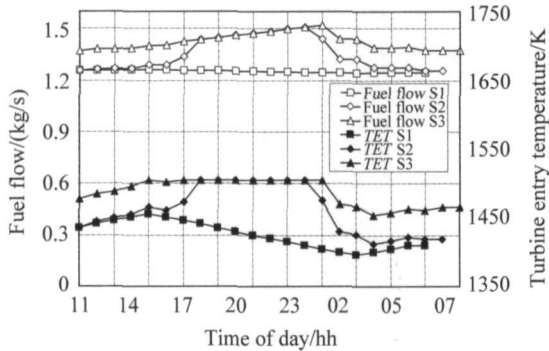


Fig. 2 Gas turbine engine fuel flow and TET characteristic

Scenario S2 shows the effect of a storm that takes place during the journey. The ship leaves harbour and nearly immediately a storm starts. This hampers the progress of the ship. To keep the service speed, the engine needs to deliver increasingly higher levels of power. At 1800 hours, the maximum power of the engines is needed. From 1800 to 2400 hours the engine is run at maximum power. This maximum power increases because as ambient temperature falls, an engine rated on temperature delivers higher power. However this maximum power is not enough to allow a constant ship speed to be maintained. The ship speed thus falls to slightly below 19 knots. As the storm abates, the ship speed starts to rise gradually to the service speed of 29 knots. When this is reached, the engine power is gradually reduced given the lessening resistance from the rough sea. When the ship arrives in port after a slightly longer journey, the sea is calm again.

In scenario S3, the hull of the ship is fouled, therefore at any speed it presents a higher resistance to the motion of the ship. The ship makes the journey through the same storm of scenario S2. It can be seen that at any point, higher engine power is needed to propel the ship through at sea. When the maximum engine power is reached, the effect of hull fouling manifests

itself as a lower speed than that of S2. For each of the three scenarios, the fuel consumed and the journey time is summarised in Table 4.

Table 4 Fuel consumed and journey times ^[10]

Scenario	Fuel consumed	Journey time
S1	93.3 tonnes	20 h 41 m in
S2	106.7 tonnes	21 h 56 m in
S3	113.3 tonnes	22 h 04 m in

4 The economic and risk analysis

The information obtained above can then be used to carry out an economic analysis. The economic analysis example discussed in the case study below was carried out for a combined cycle gas (CCGT) turbine power station and is shown in Fig. 3.

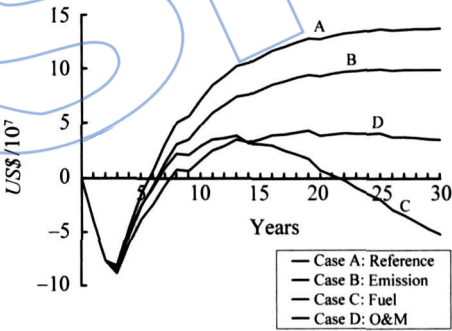


Fig. 3 Economic analysis- combined cycle gas turbine (CCGT) investment

The power plant analysed was a state of the art gas turbine and its associated steam system. Four scenarios were examined. The first (Case A) is a reference scenario. It exhibits the usual shape of a large investment. For the first few years, a large increasing negative cash flow is exhibited. During the third year, it reaches the nadir and as the power plant produces electricity that is sold, revenues accrue and the cash flow curve gradient becomes positive. In the sixth year, the investment has broken even and starts to produce a profit. The discontinuities in the curve show the year in which heavy maintenance takes place. In these years the plant is shut

down, less revenue is produced and a large maintenance payment is made. The other three scenarios examined were:

- Case B– Emissions tax
- Case C– Fast fuel cost inflation
- Case D– High operation and maintenance cost

These three scenarios show how the performance of the investment degrades when the realities of the project economics are different to those projected in the reference case.

It would be, of course, possible to analyse a vast number of scenarios to explore different sensitivities of the project. The alternative adopted at Cranfield University was to use stochastic methods and to associate probability distributions to key inputs such as the:

- Electricity price
- Fuel cost
- Operations and maintenance costs
- Interest rate
- Other relevant factors

The outcome of this stochastic analysis is shown in Fig. 4. Here the frequency and the cumulative frequency of the outcomes in terms of

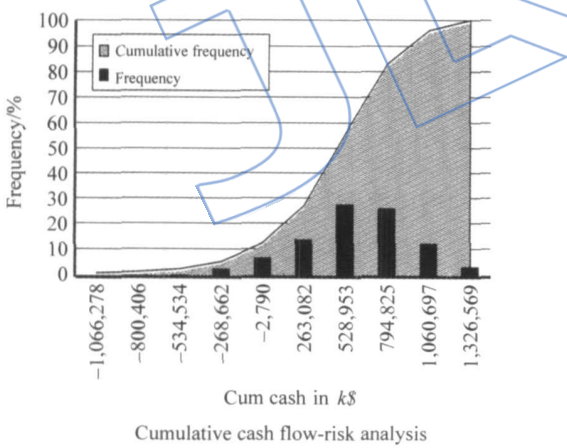


Fig. 4 Risk analysis– CCGT investment

nett present value (*NPV*) are shown. For example, the frequency distribution shows that the probability of achieving a *NPV* of about US \$ 600m is about 0.3 or 30%. The cumulative frequency curve shows that the probability of having a positive *NPV* is larger than 80%.

5 The environment analysis

The information yielded by power systems,

such as those described earlier, can also be used to produce emissions predictions. The example presented in the case study which follows, (based on Ref. [11]), is that of a round trip of a large civil transport flying between London and Tokyo. The frequency is ten flights per day. An appropriate aircraft model was produced. This was linked to an engine model created in *TURBOMATCH* and coupled to a combustor model to predict emissions of different types. The aircraft engine combination was coupled to a world weather model. The flights were segmented into time intervals to reflect changes in ambient conditions and the weight and altitude of the aircraft.

A typical outcome is shown in Fig. 5. This shows the spread of one of the pollutants after a year of the day when the flights took place. The two higher concentrations of NO_x correspond to the need to run the engines at high temperatures in the take-off at London and Tokyo.

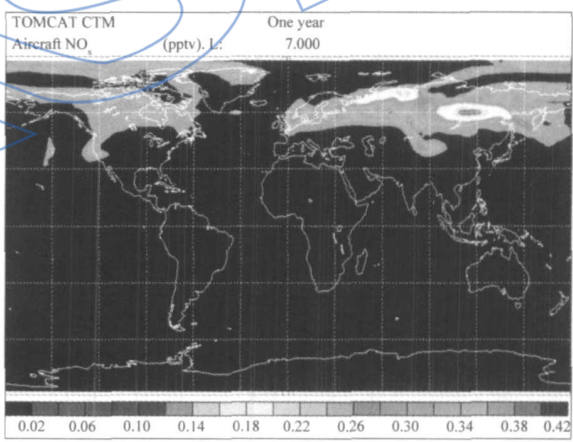


Fig. 5 NO_x emissions in parts per trillion– volume (pptv) for a London– Tokyo round trip

6 The optimisation

Another very useful feature that can greatly strengthen the application of the *TERA* framework is the inclusion of an optimisation process to compare power plants optimised for a particular duty, to ensure that each contender is examined in its best light. Fig. 6^[12-13] shows a schematic diagram of the optimisation process. For the example described, in the case study which follows, the gas turbine cycle is optimised.

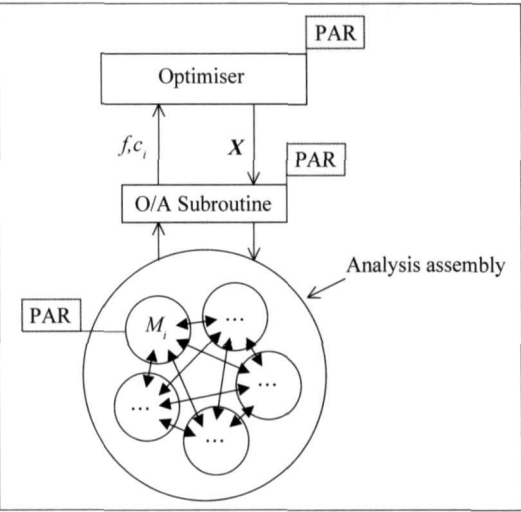


Fig. 6 Scheme of the optimisation process

Fig. 6 shows the relationship between the optimiser and the technical modules. The optimiser receives output information from the evaluation of the concept under investigation. This information provides the basis on which a concept will be judged and it may include fuel burn, economic results and emissions information. The optimiser will evaluate these against an objective function and compare the results obtained with results from earlier iterations. It will then return appropriate data to improve the input factors for the process, for example the design point cycle parameters such as pressure ratio, bypass ratio and others.

Two examples of such an optimisation are shown in the case studies which follow. The first, (Fig. 7) shows how an optimisation can deliver a detailed trade-off study. In this case, as the objective function changed from one heavily weighted in favour of *SFC* (specific fuel consumption) to one favouring the reduction of global warming potential (*GWP*) a curve of optima was produced. The curve shows the locus traced by the optima as the objective function changes. It can be observed that, initially, for a relatively small rise in *SFC* there is a useful reduction in global warming potential. This arises because the optimum power plant has a progressively lower combustion exit temperature with a consequent reduction of thermal efficiency and an increase in *SFC*. This lower combustion tem-

perature also gives a lower *NO_x* signature. It is this significant reduction in *NO_x* that brings about the reduction in *GWP*, offsetting the increased *CO₂* effect resulting from higher *SFC*. As engines with progressively lower combustor exit temperature are considered, the benefit becomes progressively smaller.

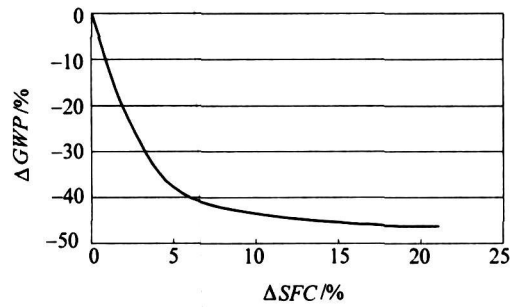


Fig. 7 Trade off study of a civil turbofan
 ΔSFC (%) is the increase in *SFC*, ΔGWP (%) is the change in global warming potential (*GWP*)

A result of the second optimisation case study is shown in Fig. 8, which illustrates the comparative benefits of the following two power plants:

- Intercooled recuperated
- advanced conventional

The examination is carried out for aircraft for different sizes. Scale factor 1 corresponds to a long range passenger aircraft of about 400 tonnes take off maximum weight. The scale factor indicates the denominator with which the mass of the aircraft is divided to identify the size of the corresponding smaller aircraft. So for example a scale factor of 2 indicates an aircraft of 1/2 the size, i. e. about 200 tonnes.

The power plants were optimised for each aircraft size. What the results show is that, for the same technologies, the intercooled recuperated power plant is more efficient for the smaller aircraft. Conventional engines, due to their small core size need to be designed with relatively low pressure ratios. For larger aircraft, the conventional turbofan can benefit from higher pressure ratios resulting in a higher thermal efficiency and lower fuel burn. The factor *K* indicates improved heat exchanger technology that enhances the prospects of the intercooled recuperated engine.

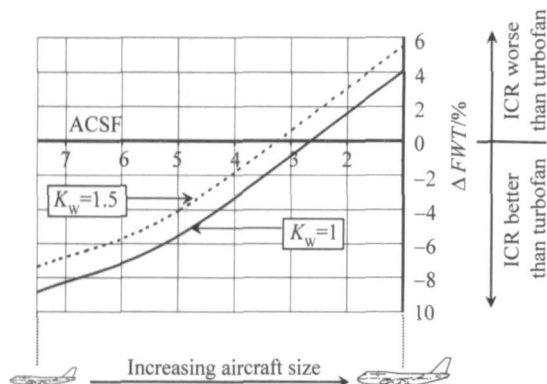


Fig. 8 Civil aircraft propulsion: comparison of ICR and conventional turbofans:

- ACSF is the aircraft scaling factor
- $\Delta FWT(\%)$ is the change in block fuel weight
- K_w is a technology factor

The above exercises give a flavour of the type of analysis that can be carried out through the deployment of appropriate TERA methods. The cases presented illustrate the results that can be obtained for specific power and propulsion systems in land, sea and air applications.

7 Conclusion

This document outlines a description of the TERA (technoeconomic environmental risk analysis) for advanced power systems. This method, developed by Cranfield, can consist of three layers of models. The first (and more complex) consists of the suite of performance models of power plants. The second incorporates emissions, environment and economic models. The third contains two aspects of risk analysis, technological and economic.

The availability of this method makes an early contribution to a complex decision process in expensive products with a long life cycle. The TERA offers increased confidence that research investments and power plant selection decisions are made in a systematic and consistent manner taking into account local conditions.

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