A Platform-Focused Power and Energy Modelling Capability for Submarines

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ABSTRACT

Maximising efficient use of the limited energy stores aboard a vessel is pivotal in achieving optimal operational performance. In the case of diesel-electric submarines, the complex nature of power systems and operating behaviours means that the most useful assessments of energy use are likely to be produced when accurate and adaptive models of power and energy systems (and the onboard systems they supply) are coupled with a robust and detailed model of the platform as a whole.

To provide this capability, a framework of granular, physics-based power and energy system models was developed and embedded into DST's mature and validated Integrated Platform Systems Model (IPSM). The new models apply an 'energy balance' approach to the platform, where the losses incurred at each phase of energy use are fully accounted for, including the energy consumed in dissipating waste heat flows.

Applications for the tool include performing objective comparisons of platform-level or component designs over specified missions and environmental conditions, as well as identifying suitable targets for recuperation of electrical energy from sources of heat. This capability is demonstrated via an analysis of the impact of seawater temperature and the characteristics of installed cooling systems on the energy consumption and mission performance of an example diesel-electric submarine.

INTRODUCTION

Maximising the efficient use of onboard energy stores is a critical part of optimising the operational performance of a platform. Energy conserved may then either be spent on improving performance characteristics like range, endurance, availability or transit speeds, or conserved to reduce fuelling costs, and potentially improve machinery life and maintenance intervals via lighter usage schedules. In addition, if design or technology changes are integrated sufficiently early in development, it may be possible for a smaller or cheaper design to achieve the same operational targets, or for capabilities to be extended on the same platform.

In the case of diesel-electric submarines, the complexity of power systems and operating behaviours often obscures the relationship between component-level changes and platform level performance impacts. For this reason, obtaining defensible assessments of the potential for emerging energy technologies to improve platform performance requires a model that integrates accurate and adaptive modes of power and energy systems with a robust and detailed model of the platform as a whole.

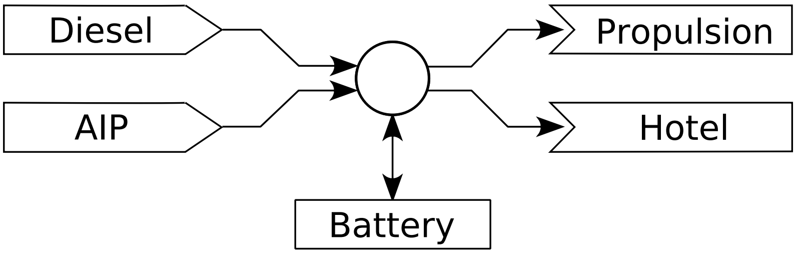

Figure 1: Top level electrical energy producers and consumers in an IPSM platform model.

DST's Integrated Platform System Model (IPSM) provides the required platform modelling capability, along with a framework for exercising these platforms via a library of mission templates and study designs. The IPSM also has a record of contribution to capability assessment studies spanning the life cycle of naval platforms, encompassing initial concept development and requirement setting, competitive evaluation processes, trade-off studies, and operational analyses [1,2].

The IPSM already includes a power and energy model that considers battery capacity, air-independent propulsion (AIP) reactant and diesel fuel reserves, energy conversion efficiencies, and variable propulsion and hotel loads. However, in this base model the systems interact only via electrical power delivery (waste heat flows are ignored), and the hotel load is modelled as a monolithic power requirement (Figure 1). This design is sufficient for assessing and comparing platforms where gross electrical loads and efficiencies are known (e.g. [3–5]), but detailed investigation of power and energy technologies requires more granularity in the model.

The present work therefore describes the development of a dynamic, modular hotel load model for use with the IPSM, incorporating a robust treatment of the costs and potential benefits associated with waste heat flows. The model applies an 'energy balance' approach to this problem, where inter-system energy transfers and losses incurred at each phase of energy use are fully accounted for, including the energy consumed in waste heat dissipation. In addition, the model is capable of identifying and quantifying opportunities for the recuperation of electrical energy from sources of heat.

Use of the updated tool is then demonstrated via a small study. This study examines the impact of seawater temperature and the characteristics of installed cooling systems on the energy consumption and mission performance of an example submarine, with the results used to suggest how the tool may be employed in future investigations.

THE NEW 'DYNAMIC HOTEL LOAD' MODEL

The intent of this new model is to decompose the monolithic hotel load, and to account for the influence of inter-system dependencies and waste heat management on the total energy consumption. As a result, each major system (e.g. combat, habitability, HVAC) is modelled separately, but interactions between the systems via electrical, thermal and other energy transfers are considered. The following sections detail the model structure for an individual system, and how these systems are then integrated into a complete model.

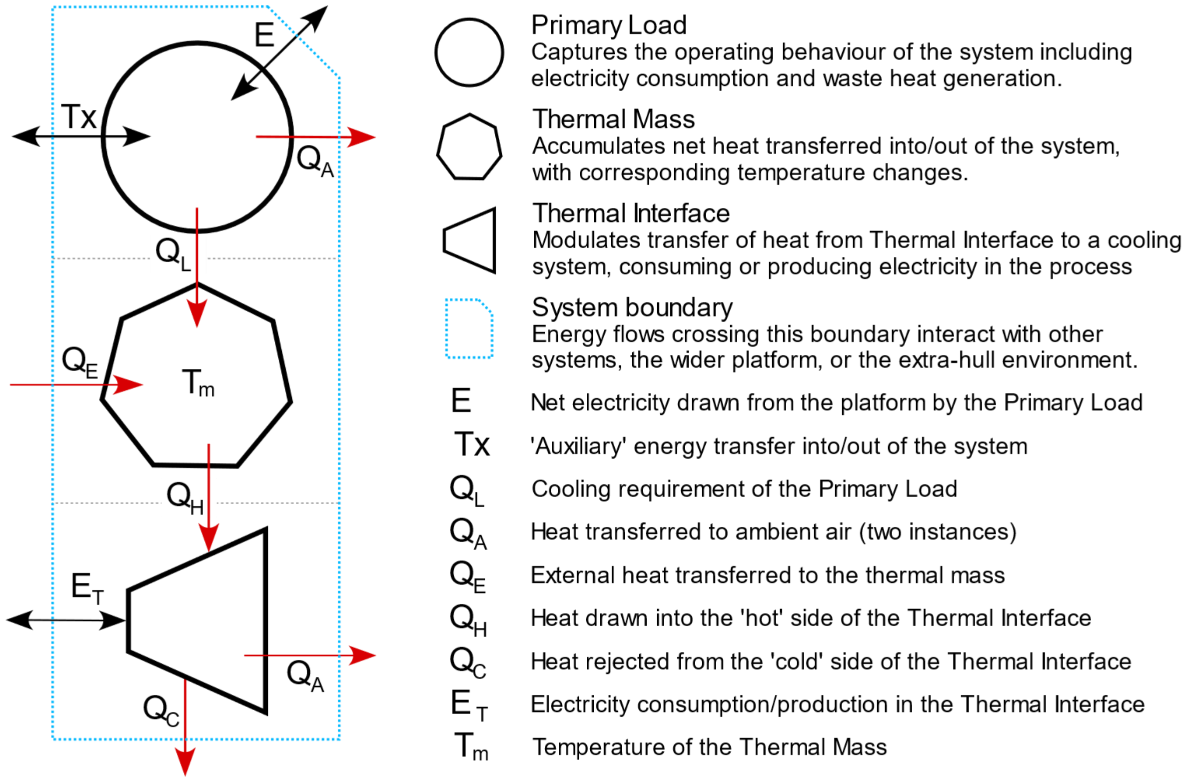

Figure 2: Schematic of energy flows for a single system

The Primary Load

The Primary Load (the circle in Figure 2) is responsible for determining the system's 'primary electrical demand' (E), and how this energy is further distributed. E represents the electricity consumed in accomplishing the systems primary task, and may be programmed to react to the present operating state of the platform (such as its speed, depth, or the nature of its current objective), or even to the activity of other systems in the network. For example, the HVAC system energy use may vary as a function of cabin temperature, the Combat system in response to the nature of current operations, or the Habitability system according to crew numbers and activity.

These primary electrical demands usually constitute the largest contribution to total hotel load, but the model is constructed to account for all energy flows to assess their individual contribution. This means that the net energy entering the Primary Load must be zero, i.e. $E + Tx + QA + QL = 0$ (Figure 2).

In this equation, Tx (the auxiliary transfer link) is used only rarely, but captures significant non-thermal exchanges between hotel systems (e.g. power supply relationships), or between a hotel system and the environment (like signal transmission or material ejection from the submarine). Finally, the net energy received via E and Tx is dissipated via Q_A (convection to ambient air) and Q_L (transfer to the coupled thermal mass).

The Thermal Mass and Heat Dissipation

Heat arriving in the Thermal Mass object (heptagon in Figure 2) via Q_L is combined with energy flows Q_E (heat transfer from externally-linked systems) and Q_H (heat removed from the mass by the Thermal Interface object) to determine net heat flux, causing T_{mass} to change accordingly. Q_E is particularly important for cooling systems, which must accept waste heat from other parts of the hotel load, while Q_H is controlled by the Thermal Interface object.

The Thermal Interface is responsible for mediating heat transfer between the Thermal Mass (connected via Q_H) and a coupled cooling system (connected via Q_C). The interface may be a simple heat exchanger, or an energy-conversion device such as a refrigeration system or a heat engine (like a thermo-electric generator or Rankine cycle). This flexibility allows straightforward comparison of the impact of a chosen technology on the energy demands of the system, and in turn the platform.

As heat passes through the interface, electrical energy may be produced or consumed (E_T), separate to the primary electrical demand above, with some heat potentially lost to ambient air (Q_A). The rate of energy transfer — as well as the efficiency of energy production or consumption — depends on the characteristics of the interface and the relative temperatures of the thermal mass and coupled cooling system.

Overall Model Structure

In the above sections, energy flows were discussed primarily in the context of a single system, however the Dynamic Hotel Load model links all hotel systems together in a network, where the key flows crossing system boundaries (E, Tx, Q_A, Q_E, E_T and Q_C, Figure 2) each relay energy to or from the next link in the chain. The overall design of this network is based upon shipboard system descriptions in well-known publications [6–8].

The electrical links E and E_T vary independently, but in combination determine how much electrical energy the system draws from the overall platform model (Figure 1). An additional hotel system (Supply Losses, not yet discussed) monitors these electrical flows and accounts for distribution losses such as power conversion inefficiencies and cable impedance. These losses are added to the total via Supply Losses' own E and E_T terms.

The thermal links Q_A, Q_C and Q_E are all inter-system links, forming the network of thermal flows shown in Figure 3. In key systems (HVAC and the cooling systems), Q_E is used to accept heat input from other systems.

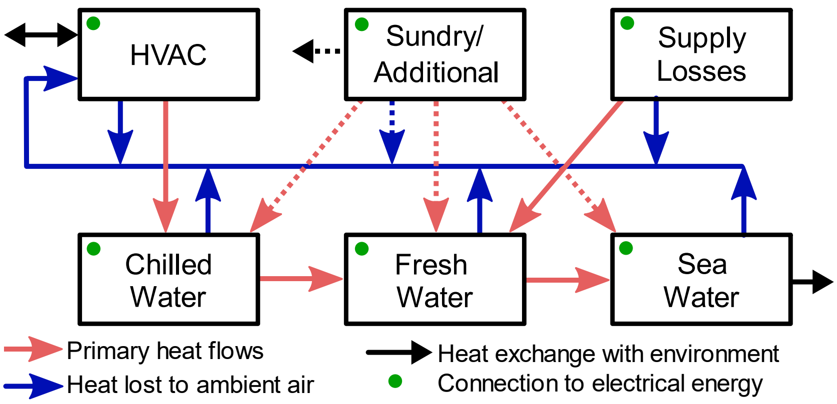

Figure 3: Structure of thermal flows for a suggested base set of platform systems. Dotted lines indicate the potential links for additional systems created using the 'Sundry/Additional' template.

In the case of HVAC, the energy accepted via Q_E is the total energy lost via Q_A across all systems (blue arrows in Figure 3). We also may note that the HVAC system is responsible for environmental interactions (black arrow) such as the induction of external air during snorts, and heat exchange with seawater across the hull.

In the case of cooling systems, Q_E constitutes the energy transferred into the system via the Q_C links of coupled systems (red arrows in Figure 3). Figure 3 also shows the cooling systems aligned in sequence in the bottom row, where each system accepts heat from zero or more non-cooling systems, and also passes energy down the chain from Chilled Water through Fresh Water to Sea Water (and ultimately out of the platform via seawater heat exchangers).

The Sundry/Additional system serves as a template for developers to account for all components of hotel load not yet captured by the other five systems. In the simplest case, all other behaviour could be aggregated into a single 'Sundry' system. However, the template may also be used to add as many hotel load systems as required to reach the desired level of resolution. Each such system may then be coupled to the appropriate cooling system (or systems), and set up with its own specific behaviours. For example, a model developer may choose to create separate models for habitability systems, ship services (like high pressure air, hydraulics or trim and balance), or to break a larger, complex system like the Combat system into smaller components.

Another important use of this template is to capture the impact of powertrain waste heat (e.g. heat generated by the diesel engines, propulsion motor, battery or AIP systems) that must be managed via the hotel HVAC and cooling systems. A hotel system may be created for each major powertrain component, absorbing waste heat generated from a component's inefficiencies as appropriate. If necessary, an electrical load (E) may also be modelled if electrically-driven equipment is required to remove heat from the component.

This waste heat is dissipated in the usual way via Q_A and Q_C, with the electricity consumed or produced in this process tracked as E_T. Thus, the modeller is not only able to investigate the relationship between powertrain efficiency and hotel loads, but also to assess the effectiveness of potential technologies for recuperation of powertrain waste heat (e.g. Olshima et al. [9]).

Summary of capabilities

Figure 4 shows the main energy flows typically observed in a diesel-electric submarine. The arrows representing these flows are coloured according to type (e.g. thermal or electrical), and sized in approximate proportion to the magnitude of each flow. This representation articulates that any energy conversion inevitably involves some degree of loss, and that these losses (and hence opportunities for improvement) are numerous and widespread.

The Dynamic Hotel Load model, in conjunction with the wider IPSM, is thus useful in providing the ability to investigate:

- how a specific system behaves within a particular scenario,
- how a system's behaviour changes across multiple scenarios,
- how a system is impacted by energy flows from the environment or other systems,

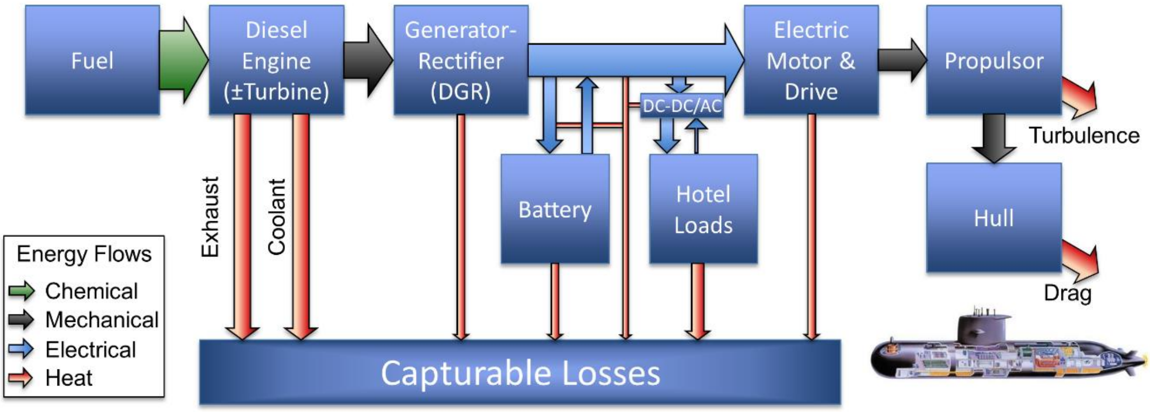

Figure 4: Sankey diagram of major energy flows in a diesel-electric submarine

- the energy demands of waste heat handling equipment,
- the impact of substituting system or component technologies,
- the impact of adding or removing complete subsystems,
- how and where energy may be recovered from waste heat flows.

The following section demonstrates one such investigation.

EXAMPLE APPLICATION

Definition of mission and metrics

Each individual IPSM simulation requires specification of both a platform and a mission. A mission defines a series of tasks that must be completed in order. Each segment has its own criteria for completion (e.g. distance travelled, fuel used or time on patrol) and associated operating constraints and CONOPS policies including: operating speeds, snorting strategy, environmental conditions, threat environment and required energy reserves at completion of the stage.

Figure 5 shows the mission considered in this paper, in which the platform must:

1. Transit from the base to the Operational Area (OA), including a 'Constrained Transit' (CT) segment characterised by increased detection threat,
2. Patrol in the OA, leaving to snort safely as required, until the allocated time or fuel is exhausted,
3. Return to base via Open Ocean Transit (OOT) once the patrol is complete.

The IPSM records time traces of all significant variables, and produces additional reports, graphs (like Figure 6) or summary metrics as requested. Two such metrics we consider in our example are Operational Area Effectiveness (OAE, the fraction of time in the OA leg spent in the patrol box), and Mission Effectiveness (ME, the fraction of total mission time spent in the patrol box).

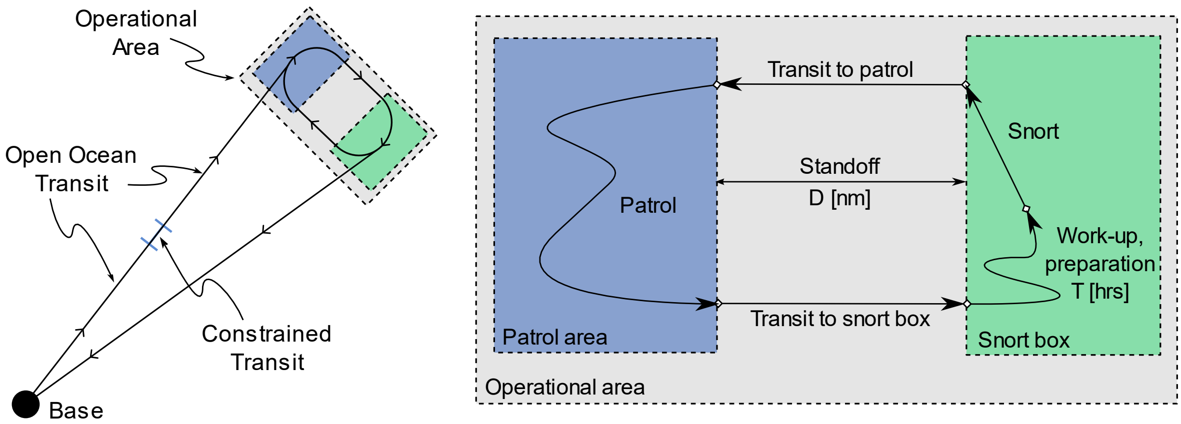

Figure 5: Example mission structure, with detailed view of the Operational Area.

Baseline scenario

Figure 6 was obtained by executing a simulation of the above mission with an example platform and a baseline parameter set. Some notable performance features are:

- During the transit legs at the start and end of the mission, battery discharge rate is high as a result of the higher speed and propulsion load, contributing to approximately daily snorting. No limitations on snorting apply in the open ocean.
- Just before the short 'constrained' transit, the mission requires the submarine to replenish the battery to a suitable level before proceeding into the area. Once the CT leg is commenced, a more conservative minimum battery level is applied in this leg (blue shading), as in the OA. Snorting is avoided where possible.

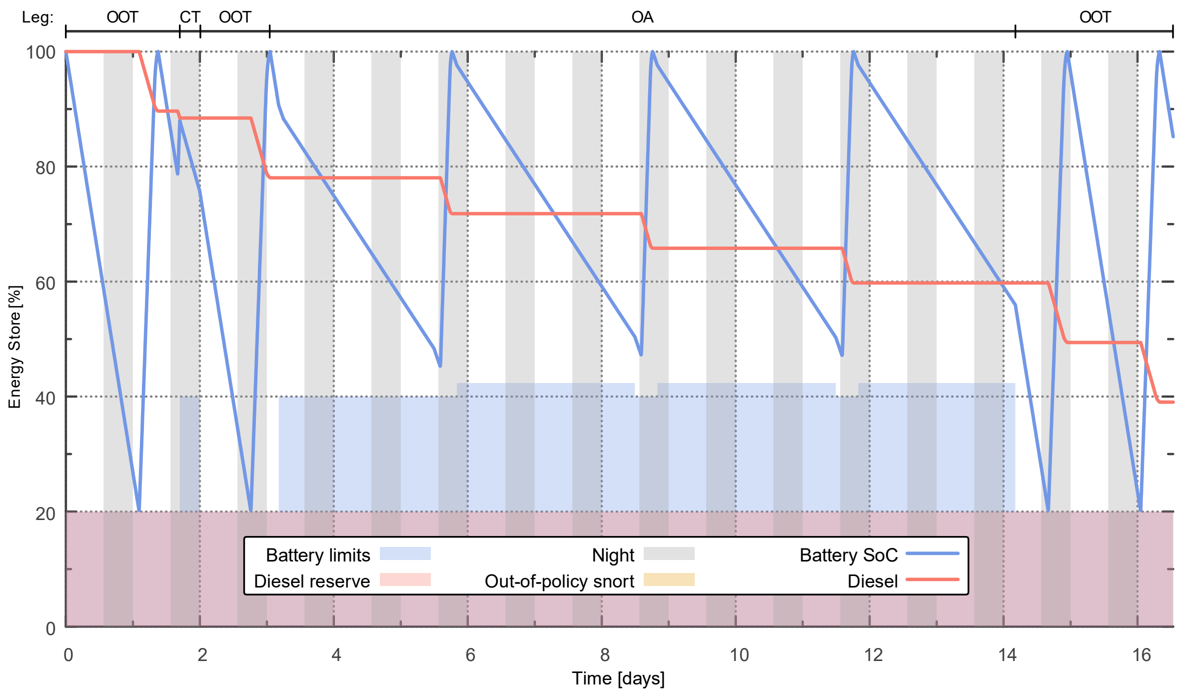

Figure 6: Evolution of energy store levels over the scenario illustrated in Figure 5, as generated by the IPSM. Mission segments depicted: Open Ocean Transit (OOT), Constrained Transit (CT) and Operational Area (OA).

- In the operational area, propulsion demands are lower, and snorting is only required once every three days. The submarine leaves the patrol box before the battery is fully depleted to ensure a) there is sufficient charge to transit to the snort box, and b) snorting will only occur at night as preferred (grey shading). No 'out-of-policy' snorts occurred in this simulation. Transits to and from the snort box are visible as short periods of increased battery discharge rate before and after each snort.

These results are repeated in the top-left plot of Figure 7, which provides similar summaries for two more scenarios, as well as some additional outputs: temperature traces for seawater, freshwater coolant and chilled water coolant in the second row, and the major thermal flows through the chilled water cooling system (with magnitudes normalised to unity) in the third. The two alternative scenarios are introduced in the sections below, and Table 1 at the end of this section summarises the inputs and key performance outcomes for all three cases.

In this first scenario, T_{sea} is relatively low at 5°C, resulting in favourable operating conditions for chilled water system (the chilled water is warmer than the fresh water, which is slightly warmer than T_{sea}). This results in a low electricity demand for cooling relative to the cooling load (bottom left). The spikes in cooling load visible during snort events are a result of the diesel engines pulling in warmer surface air, increasing the demand on the HVAC system, which subsequently dumps its waste heat to chilled water.

Modifying environmental conditions

In the second scenario (Figure 7, centre column), the platform specification is unchanged but T_{sea} is raised to 30°C. This imposes two detrimental effects on platform performance. First, there is a change in the rate of heat transfer between the submarine's hull and the seawater outside, worsening the load on the HVAC system. This is observable in the greater magnitude of the 'incoming heat load' relative to the first scenario (solid dark line). Second, it causes a higher freshwater coolant temperature, which in turn provides a large adverse temperature gradient for the chilled water cooling system's refrigeration equipment. This causes a reduction in chiller performance, resulting in electricity consumption that is a much greater fraction of the incoming heat load (solid grey line).

Overall, the impact of this higher electricity demand on total hotel load is significant, and requires the platform to switch from a 3-day to a 2-day snorting cycle to avoid exhausting the batteries between permissible snort periods. Diesel fuel consumption has also increased. The need to spend more time snorting, and in particular transiting to and from the snort box, has a measurable impact on the platform's overall performance (Table 1). Specifically, chiller energy use has more than doubled and the OAE and ME performance metrics have dropped by almost 5% in relative terms from Scenario 1 to Scenario 2.

Modifying system performance

While it is difficult to mitigate heat transfer between the hull and the ocean, it may be possible to upgrade the refrigeration plant within the chilled water system. In the third scenario (right-hand column of Figure 7), the environmental conditions are the same as in the second scenario, but the chiller is now operating with improved efficiency.

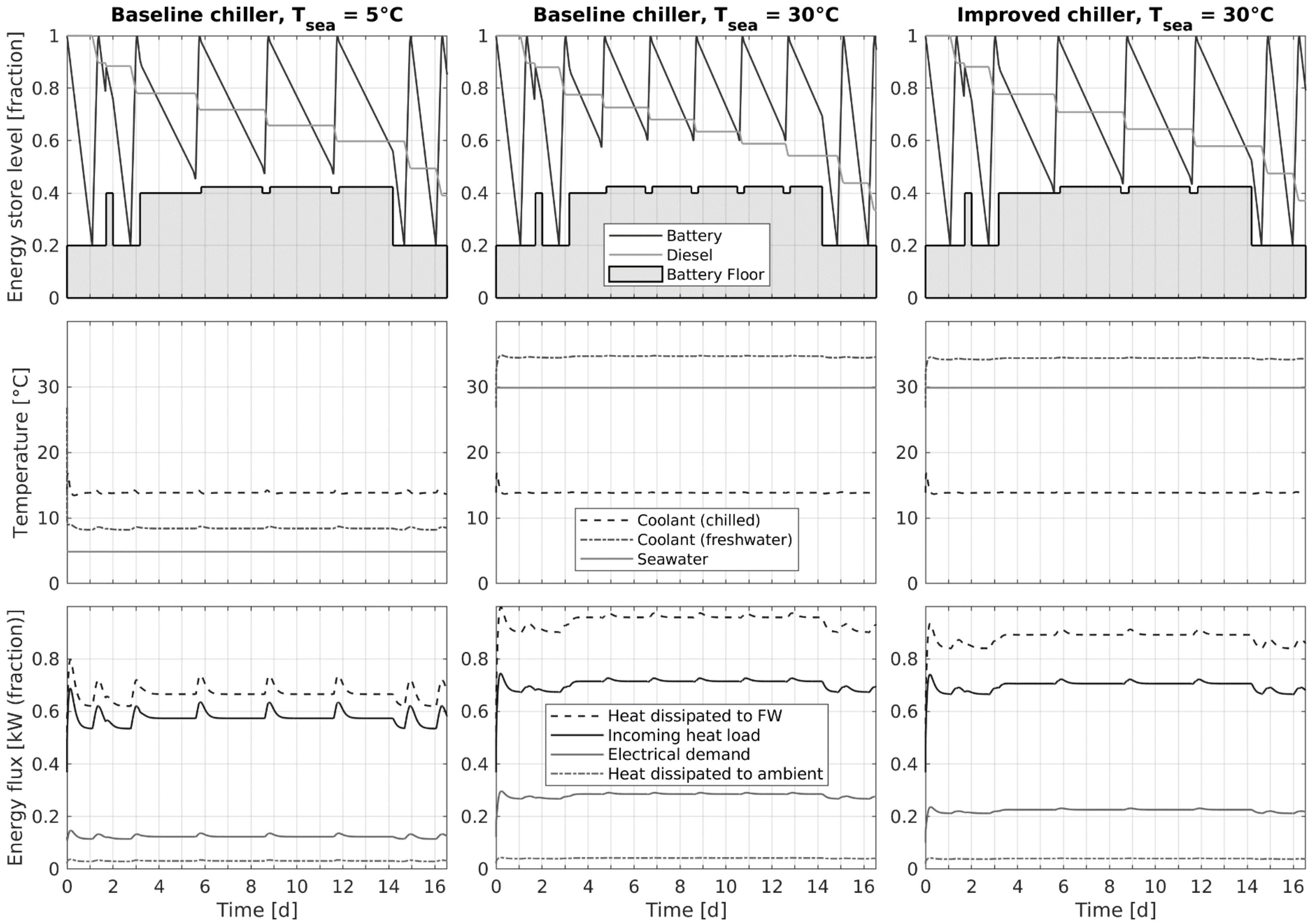

Figure 7: Simulation results for the three scenarios under examination.

Table 1: Summary of simulation inputs and results for the three scenarios considered

	Scenario 1	Scenario 2	Scenario 3
Sea temperature	5°C	30°C	30°C
Chiller performance	Standard	Standard	Improved
Mission duration	396.7 h	397.0 h	396.9 h
Chiller energy use (mean)	12.4%	28.1%	22.2%
Snort count (total/OA)	8/3	10/5	8/3
Diesel fraction remaining	39.0%	33.4%	37.1%
Time on station	237.8 h	226.8 h	237.1 h
OA Effectiveness (OAE)	90.1%	85.9%	89.8%
Mission Effectiveness (ME)	60.0%	57.1%	59.7%

This change has little effect on the incoming heat load (bottom-right), but reduces the penalty in electricity consumption of the chilled water system by around 38%, and in diesel consumption by around 52%. Significantly, the top-right plot of Figure 7 shows that this change is sufficient to return to a 3-day snorting pattern (although with lower battery reserve at the end of each cycle), and recover almost all of the penalty to OAE and ME metrics that was imposed by operating in warmer waters.

Modelling outcomes

This section presented an example of a simple, back-to-back comparison analysis achievable with the newly-upgraded IPSM. Similar analyses may of course be carried out on any number variety of platforms and scenarios. However, by leveraging IPSM's integration with Sandia National Labs' *Dakota* design of experiment tool [10], it is also possible to carry out parameter optimisations and other multi-variable analyses as required.

CONCLUSIONS

The intent and capabilities of a power and energy model developed for integration into DST's Integrated Platform System Model (IPSM) were described and demonstrated via a worked example. The new model provides a robust, granular and comprehensive framework for itemising and interrogating models of hotel systems and powertrain waste heat flows. Such studies may take the form of simple back-to-back simulations like those presented here, or more complex analyses by leveraging existing IPSM features and extensions.

As part of the IPSM, the new energy model provides DST with the capability to understand, assess and compare complete platform designs and technology insertion proposals in the power and energy domain. This is an important competency for the Department of Defence as a smart buyer, supporting rigorous decision-making and technical assurance in both new acquisition and life of type extension projects.

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