Development of Anti-/De-Icing System based on Active Thermography

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Abstract— **Ice accretion remains a pervasive challenge for infrastructure in cold climates, posing threats to both human safety and machine operability. Addressing this issue, our work introduces an innovative, automated ice detection/mitigation system leveraging active infrared thermography. This technology enables the detection of ice on low-temperature surfaces exhibiting thermal contrast. The system integrates low-cost thermal infrared cameras and gridded-gradient heaters to remotely operate and mitigate the identified ice patches. The operational workflow begins with the system mapping the region of interest, identifying iced surface patches within its field of view. Subsequently, the system makes calculated decisions to initiate mitigation measures for the detected regions. The evaluation of the system encompasses key factors such as heat transfer, power converter efficiency, and dynamic switching behaviour. The study explores the impact of two heating techniques: continuous power heating and modified pulsed power heating, conducting a comparative analysis to discern their respective efficacy. This research not only introduces an effective solution for ice detection and mitigation but also contributes valuable insights into optimizing the efficiency and performance of such systems. By addressing the challenges posed by ice accretion, our work aims to enhance the safety and functionality of onshore and offshore infrastructure in cold climatic regions.**

Keywords— ***System design, ice protection, infrared, electrothermal, remote sensing***

I. INTRODUCTION

Icing is a natural phenomenon in cold regions especially Arctic regions and ice accretion on onshore, offshore, and airborne structures poses grave damage to them in terms of system operation; consequences may lead to irreversible losses in terms of human and machine safety [1,2]. In most of the cases where exposure to cold weather is prolonged, avoiding the icing situation is simply not an option and therefore different techniques are adopted to prevent the ice (anti-icing system) or melt the ice (de-icing system). Overall system comprising an ice detection and mitigation strategy is called an ice protection system. Multiple techniques exist in literature or in practice that propose different technologies manifesting the laws of optics, physics, and chemistry to detect and prevent/melt the ice [3-6]. These techniques leverage each other's pros and cons to solve application-specific problem at hand.

Upon carefully conducted literature review and up to the best knowledge of authors an automated, energy efficient ice protection system could not be found in application. This paper presents the ongoing work conducted in this regard to achieve the desired objectives of economic, reliable and remotely operated autonomous system. Direct/indirect ice detection strategies were studied [7,8] and active Infrared Thermography (IRT) was shortlisted for its non-destructive remote sensing and wide area scan capabilities. Previous works also exist to support the proposition that long wave infrared (LWIR) cameras can detect and differentiate the fresh water and saline ice [9-12]. For the ice mitigation part, electrothermal heating is chosen to be implemented for it is comparatively efficient than other existing strategies. This system also serves as excitation technique for active thermography. Since the work is ongoing, the conceptual design and supporting preliminary heat transfer simulations are presented in the following section.

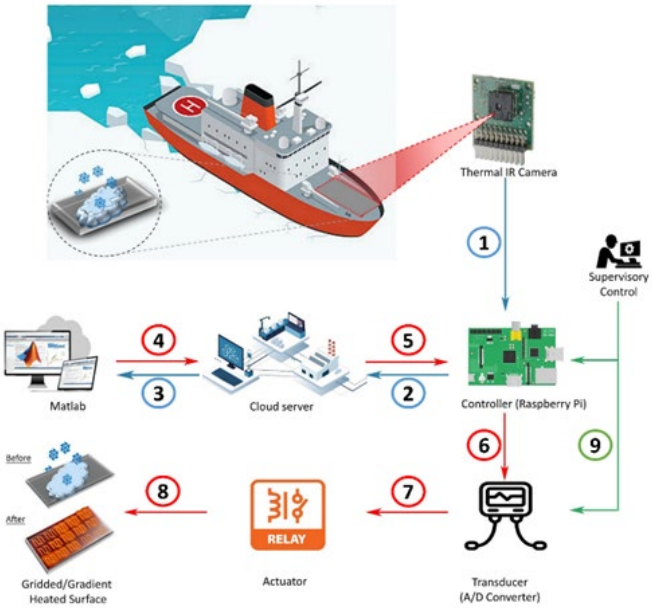
II. METHODOLOGY

System design is divided into three phases: (i) conceptual design – that presents the big picture of overall system (ii) preliminary heat transfer simulation mandatory to study thermal behaviour of heating system (iii) hardware design.

A. Conceptual Design

A conceptualised economical ice protection system is shown below in Figure 1 in which arrowheads with numbering show the sequence of operation. Starting off with an LWIR camera that focuses on the target surface prone to icing (ship deck here), the camera captures incident thermal radiation emitted by the target and the environment and sends output thermogram to the controller. Based on the decision (ice/no ice), it will send signals to energize/de-energize the transducers/relays for heating only at the locations where ice is detected. For this, a gridded heated surface comprised of small heating elements is proposed that can attain a gradient heating pattern. For research phase, remote image processing shall also be incorporated into the system. In this setup the controller shall send captured images to a cloud server from where they can be downloaded through an image processing software such as MathWorks® MATLAB. Additionally, the inclusion of supervisory control for emergency operations ensures the overall system's reliability and fail-safe operation.

One of the most significant challenges in IRT is expensive operational setup and equipment, particularly the infrared camera. The heavy cost hinders field study of icing on structures as it adds to the maintenance costs of camera in case of mishap or malfunction [1]. So, to address this issue low cost LWIR FLIR® Lepton on-chip cameras are suggested. The camera resolution is 80×60 and costs around only $250. To assess if such a low-end camera can detect ice or not, a simple experiment was conducted for comparative study between FLIR® Lepton and FLIR® T1030SC cameras; both are LWIR cameras featured with uncooled microbolometer, later one being 768×1024 in resolution and costing approx. $50000. The experiment comprised of an ice cube of known dimensions placed over a high emissive (~0.85) PET sheet supporting 75W, 230V heater (see Figure 2).



1) Image acquisition
2) Uploading images to the server
3) Downloading images for remote image processing
4) Processed image decision (ice/no ice)
5) Reading decisions from the cloud server
6) Activation/deactivation of corresponding transducers
7) Energize/de-energize relays
8) Switching ON/OFF embedded heaters in the surface and supplying controlled heating
9) Supervisory control for emergency operation/system failure

Fig. 1 Conceptual design of proposed ice detection and mitigation system [13].

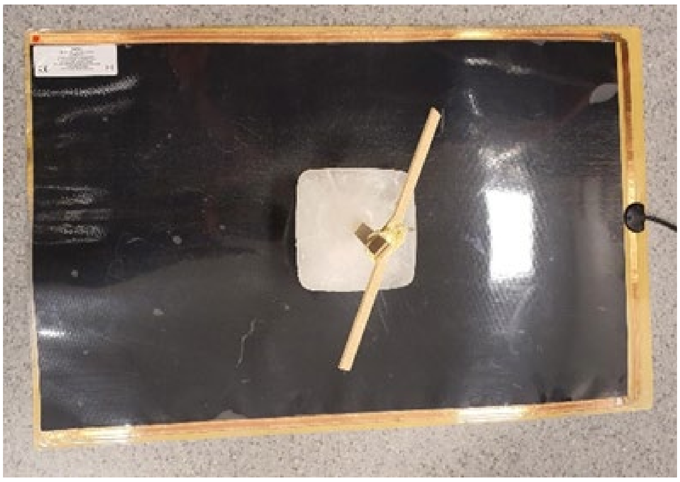
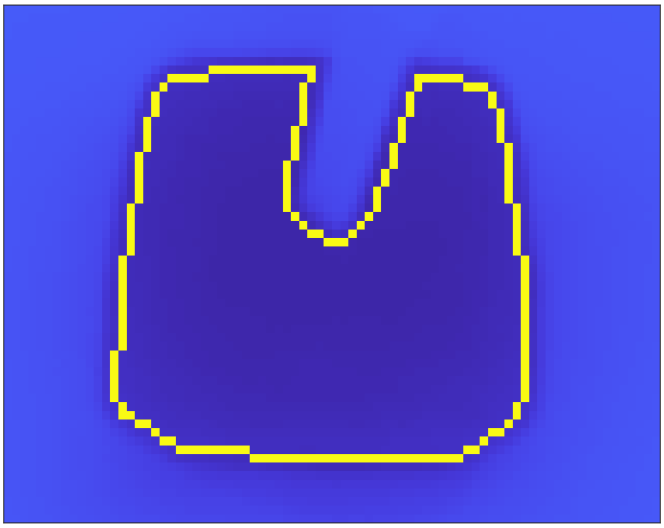
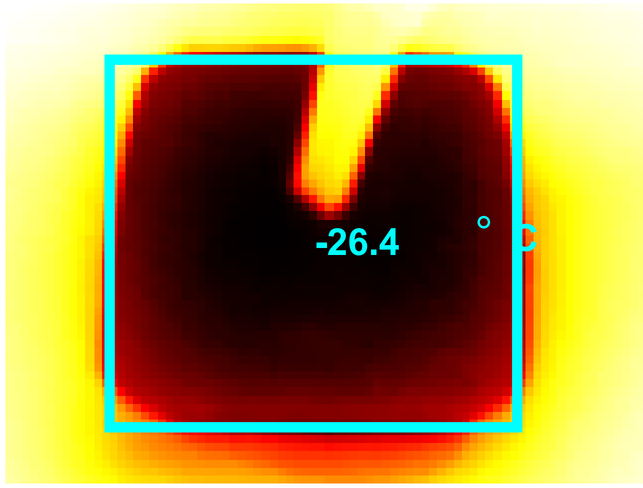


Fig. 2 Ice cube placed on PET sheet for infrared thermography analysis of low- and high-resolution images [13].

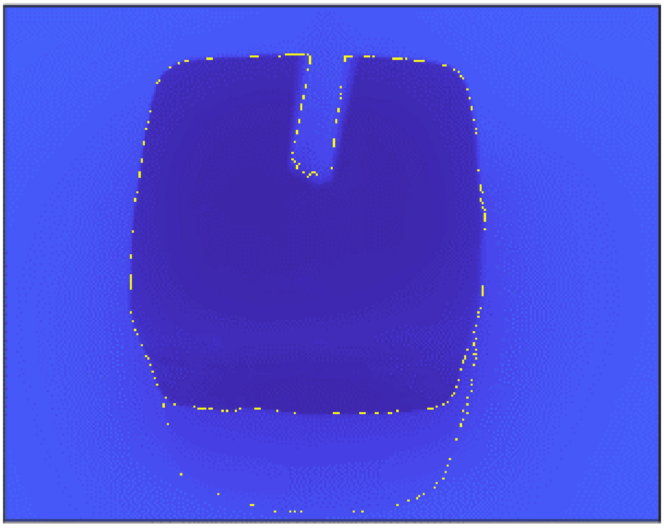
The ice cube was observed with both the cameras and their results were subjected to image processing in which goal was to segment the ice edges. Closing morphological operation was performed along with Canny edge detection technique to successfully achieve the desired result. It was observed that both the cameras were able to capture and detect the ice after image processing. However, from the accuracy point of concern, FLIR® T1030SC camera is more accurate than the Lepton, which is why the difference of 2°C in mean temperature is apparent (see Figure 3).



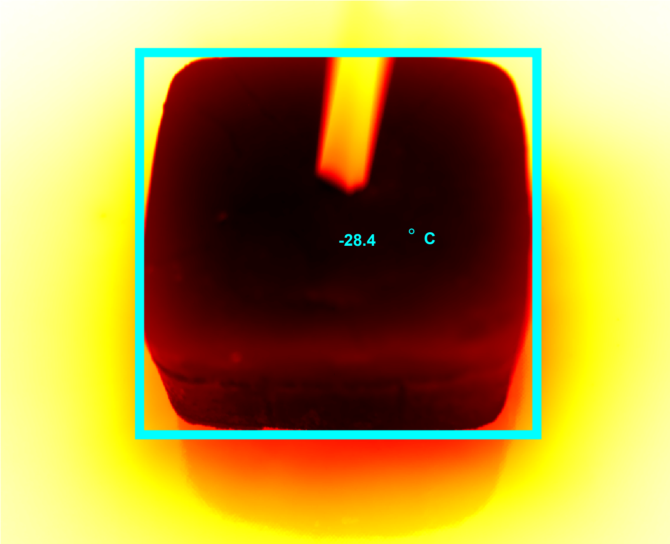
Lepton (80×60) – edge detected image



Lepton (80×60) – average temperature of segmented region



T1030SC (768×1024) – edge detected image



T1030SC (768×1024) – average temperature of segmented region

Fig. 3 Final results after applying morphological operations on thermal IR images [13].

B. *Simulation*

For ice mitigation system the idea of gridded, gradient heating elements is presented, according to which the target surface will be accompanied by multiple adhesive heaters. For energy saving heaters at only those locations will be switched on that experience icing. This concept is first simulated in software before proceeding for actual hardware design.

For this purpose, a two-dimensional aluminium surface (100cm×50cm) with subzero temperature regions (representing ice) is simulated in MATLAB®. Corresponding parameters for aluminium sheet and heaters are taken into account and Finite Difference Method (FDM) is applied to solve 2D heat equation. Boundary conditions are 258K for air temperature whereas the temperature for iced region is taken as 253K in the initial conditions. For illustration, figure 4 below shows 4 out of 18 heaters of equal dimensions (10cm×10cm) activated for studying heat transfer. Heating is activated at t = 5s. This case is chosen to mimic a condition when icing will only need to be removed at these particular heater locations. Pattern at t = 4s shows the temperature diffusion across the perimeter of iced region.

Figure 5 below displays contour plots after the heaters are activated. It is assumed that heat transfer is only taking place through conduction without any heat loss and heaters turn ON in step function pattern (with constant 400K temperature assumed). Temperature evolution seeks to achieve thermal equilibrium over aluminium sheet. Simulation is run here for 500s; if ran for an extended time that stage can be observed in a contour plot with uniform temperature of 400K over whole surface.

C. *Hardware Design*

As a part of hardware design implementation electronic assembly including two Lepton IR cameras are planned to be fixed in a waterproof polycarbonate plastic box with IP67 rating. Lepton cameras feature 50° horizontal field of view (FOV) so two cameras can cover an extended view. A 3D

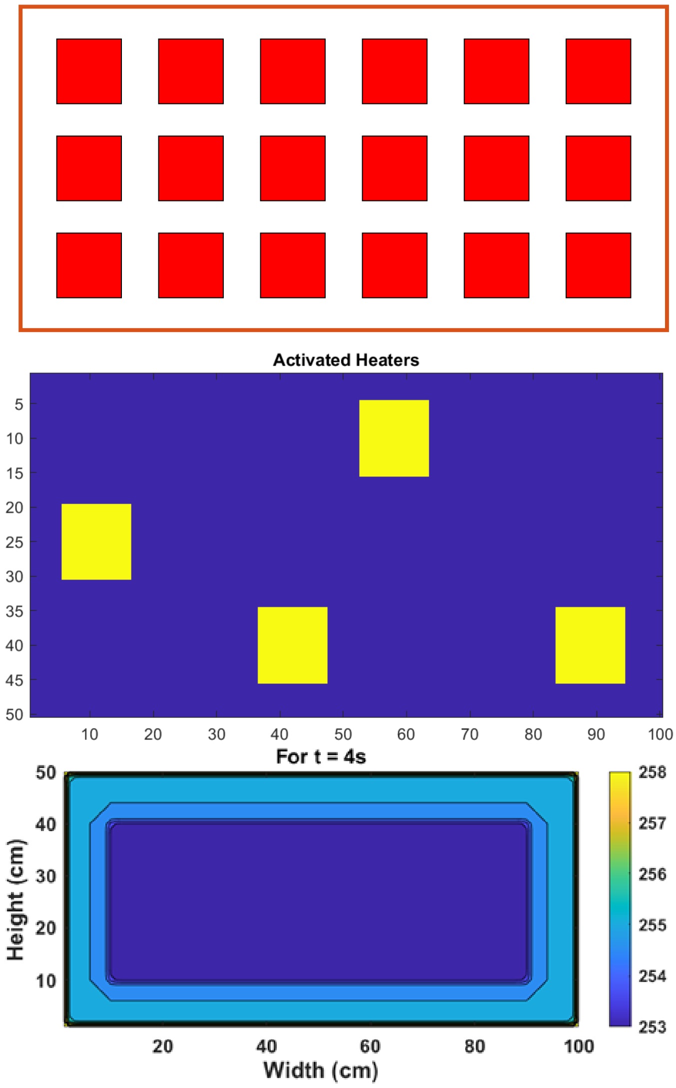


Fig. 4 Eighteen gridded heaters over aluminium surface and considering 4 out of 18 activated heaters for simulation. Last image shows thermal pattern at t = 4s in the presence of ice when heaters are not yet activated.

printed casing is developed for them that houses camera module and germanium window for the camera lens. germanium is chosen for its high transmission rate for LWIR. The box is also supposed to house cable connections for controller and relay modules for the activation of heaters. Figure 6 shows a 3D printed camera housing; a red-shaded exposure can be seen in front of one of the cameras, it is the installed Germanium window.

A thin aluminium target surface (100cm×50cm×0.05cm) is prepared for electrothermal heating supplied with 18 gridded adhesive heaters (in a matrix of 3×6). Since aluminium itself is highly shiny, its one side facing the cameras is polished with black acrylic spray which has a high emissivity value (~ 0.9) as shown in Figure 7. This step is important to perform as otherwise reflected radiation can deceive thermal camera.

Final results are expected to arrive after the complete implementation of remaining system that include communication between controller and software. The hardware setup shall be tested in laboratory as well as on the field.

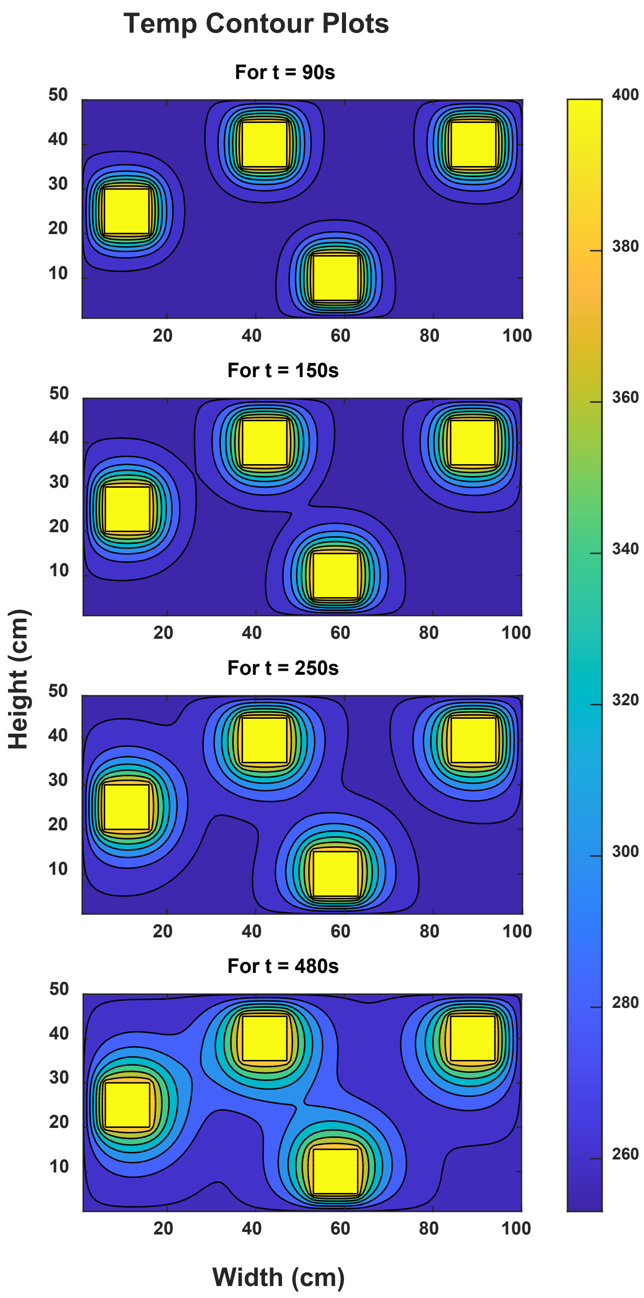
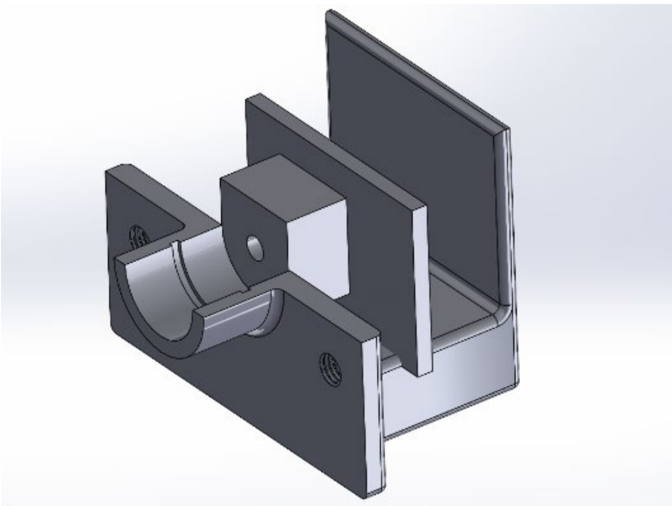


Fig. 5 Heating pattern for activated heaters.



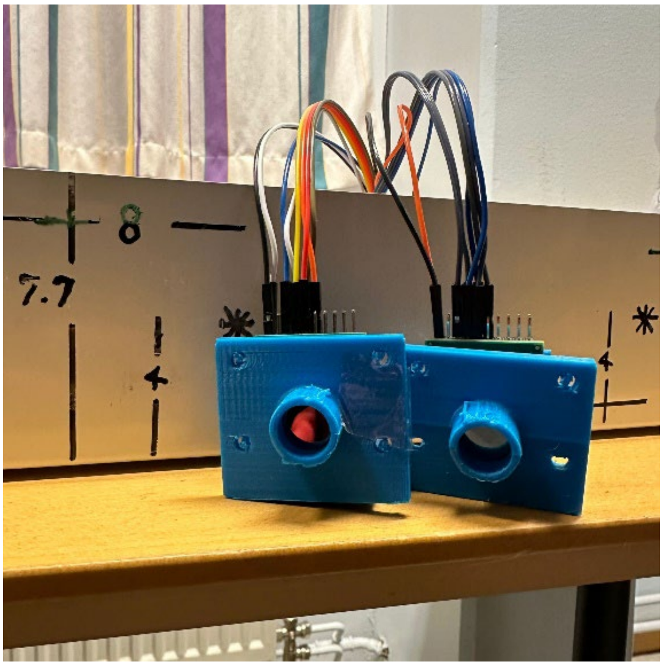


Fig. 6 3D printed FLIR® Lepton camera housing.

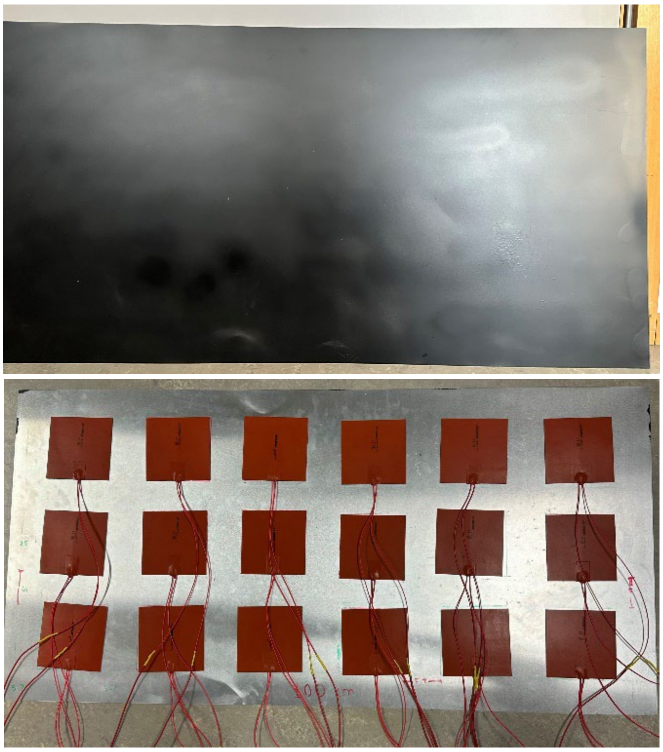


Fig. 7 Polished side and heaters side of aluminium sheet.

III. Conclusion

Build-up of ice on structures poses risks to structures in aviation, energy, transport, and marine sectors. In this regard, a conceptual ice protection system based on active infrared thermography as its ice detection module and electrothermal heating as its ice mitigation module is presented. The work is underway and currently showcases heat transfer simulations and completed hardware setup. Final results are awaited till the completion of whole setup. The work addresses the ice accretion challenge faced by different surfaces and structures in cold climate regions and aims to automation with cost-effectiveness and energy efficiency.

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