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SIMPLIFIED TECHNIQUES FOR LOW GRADE HEAT ENERGY MANAGEMENT - INDUSTRIAL APPLICATION

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ABSTRACT

Reducing industrial low grade heat generation and waste leads to improved energy efficiency, decreased environmental emissions and reduced fuel costs. However it is an area that is recognised as being underexploited. Many studies have been carried out developing methodologies and techniques for the reduction and reuse of the waste heat. However the techniques are typically specific to a process or industry platform. Additionally success levels can be heavily dependent on the prior knowledge and experience of the practitioner.

This paper shows the development of a new methodology called GALGEM (General Approach to Low Grade Energy Management), which combines existing Process Integration techniques with second law of Thermodynamics analysis and heuristic rules to give a general guideline for energy management. The specific focus is on low grade waste heat. GALGEM is a simplified technique, based on the solid foundation of existing techniques and best practice. It guides practitioners through the decision making process to exclude the less effective solutions, thus reducing reliance on tacit knowledge and expertise for the predetermination of success. GALGEM is designed to be applicable across all sectors and industrial processes. The success of the technique is demonstrated in an industrial case study, a large international semiconductor manufacturing plant, highlighting direct, indirect and combined heat exchange opportunities for waste heat recovery

INTRODUCTION

Improving energy efficiency leads to reduced energy consumption, energy costs and greenhouse gas (GHG) emissions and increased competitiveness and security of supply. In addition energy efficiency enhancement can assist in compliance with environmental legislative obligations [1].

The industrial sector accounts for a 36% of the global energy demand [2]. This percentage varies depending on the individual country, for example in the United States about 33% of the total energy consumed is by industry [3], while in Ireland the sector accounts for 16% of the total energy consumed [4]. As industrial energy use is significant it is targeted for improved energy efficiency [5]. One aspect of industrial energy use as yet to be fully exploited, in terms of efficiency improvement opportunity, is the area of waste heat. Waste heat is generated in practically every process and accounts for between 20% and 50% of the initial industrial energy input [3].

In 2009 I2E2 (Innovation for Ireland's Energy Efficiency) commissioned research into the potential for low grade waste heat recovery in Irish industry [6]. The research focused on a number of manufacturing plants that were members of the I2E2 group. One of the key findings of the research carried out was that even though potentially significant quantities of low grade waste heat is generated it was essentially ignored in most facilities as an intangible resource.

The research team observed low levels of understanding in the participating companies regarding quantities of waste heat generated, why it was generated or where it was generated.

NOMENCLATURE

E	[kW]	Exergy
H	[kW]	Enthalpy
T	[K]	Temperature
S	[kW/K]	Entropy
I	[kW]	Inevitable exergy loss
P	[Bar]	Pressure

Superscripts

Q	Supply
in	External input
a	Avoidable loss
ut	Utility load
0	Refers to the environmental state
ch	Refers to chemical exergy

While the participating company representatives were familiar with techniques for the assessment of waste heat and waste heat recovery, they felt that many of these techniques were too complex or process specific for the purposes of the industries in question. It was found that there was a need for a general way in which the heat performance of a facility could be (i) assessed (ii) analysed (iii) compared to other processes/sites/facilities. This method was to be relatively uncomplicated and to draw on the strengths of already existing techniques.

The aim of the present work is to further develop the structure of the GALGEM methodology as well as to present the results of its application on an industrial case study.

GALGEM – GENERAL CHARACTERISTICS

One of the essential characteristics of the GALGEM approach is to develop a system that is not overly reliant on the tacit knowledge and experience of the engineer. The GALGEM approach was devised for the management of heat energy as a support to operation and design not as a detailed design tool.

A review was carried out of the commonly used existing techniques for heat energy management and together with some of the less established techniques. Following these investigation two methods in particular were focused upon:

Pinch analysis

Pinch analysis is recognised as being an excellent method for the assessment, analysis and design of efficient heating and cooling networks [7]. It is a well-established technique that has been used and adapted for many processes and industries. It can deliver highly efficient designs and when combined with optimisation techniques can tackle complex problems in an effective manner.

However Pinch analysis has some drawbacks. For those that are new to Pinch analysis, or who only use it on an occasional basis, it can be onerous in terms of data collection and use. This is especially true if the users do not have access to any of the many Pinch analysis software packages. Additionally if they are not familiar with the technique or process then they may have difficulty in deciding some of the factors that can affect the analysis. These factors include the log mean temperature difference (ΔT_{min}), the boundaries of the system, site specific issues etc. Even if users have the software packages available they may not have the freedom or inclination to spend time learning how to use it.

Another drawback experienced is that Pinch analysis is not always as effective when implemented in existing facilities as the opportunity to change technology or to divert streams might not exist and techniques such as splitting of streams could cause major disruptions. Importantly, for our research, Pinch analysis does not generally take into account the available waste streams in a plant. Thus, due to inexperience, the engineer might only consider waste streams after the Pinch analysis and internal stream matching has been carried out. In the case of an experienced practitioner these drawbacks are normally easily overcome as they blend their own tacit knowledge and experience with the technique to come up with a proposed solution. However in the case of the inexperienced practitioner these drawbacks could impact significantly on the efficacy of the final proposed solution. Finally if the practitioner has little or no conceptual idea of the potential saving opportunities then the assessment may not take place at all.

Exergy Analysis

Exergy analysis is a powerful technique that combines the first and second laws of thermodynamics. The exergy content of a substance accounts for the ability of the energy to do work, moving from the existing conditions to equilibrium with the environmental conditions. Engineers and Scientists use exergy analysis to examine, design and improve systems and processes. In particular exergy analysis can be used to locate and quantify the inefficiency of a process system [8].

The overall exergy consists of the mechanical, thermo-mechanical and chemical components according to the type of energy. In heat network systems usually the mechanical (kinetic and potential) exergy is negligible in comparison to the thermal exergy. In this case the total exergy content of a stream is made up of the thermo-mechanical exergy and the chemical exergy [9]:

$$E = (H - H_0) - T_0(S - S_0) + E_{ch} \qquad (1)$$

where (H) is the enthalpy, (S) the entropy, (E_{ch}) and the index "$_0$" refers to the environmental conditions. The particular conditions of the environment can be determined for each particular case, but must be consistent across the analysis carried out. If the environmental conditions are not consistent then systems or processes cannot be compared. The chemical exergy element drops out when there is no chemical reaction as part of the heating or cooling process. Then in Eq. (1) only the thermo-mechanical exergy remains. This exergy can be temperature or pressure based depending on the operational conditions of the process – at constant pressure or constant temperature. In the most heat exchange networks the exergy can be determined as temperature based using the equation

$$E = (H - H_0) - T_0(S - S_0) \text{ at } P=const. \qquad (2)$$

T_0, H_0 and S_0 are determined at what is known as the environmental state.

Particular strengths of exergy analysis are the concepts of avoidable exergy loss and inevitable exergy loss. Avoidable exergy loss is the exergy that remains as a waste stream after the process interaction. No benefit to the process is derived from the avoidable exergy. The avoidable exergy is categorised as a process waste stream. Inevitable exergy loss is the definite loss transforming exergy to anergy due to the irreversibility of a process. Usually this exergy loss depends on the type of equipment and the process parameters.

Figure 1 shows a basic 'black box' process from the point of view of exergy flow. The input exergies are represented by E^{in} the external exergy input stream (i.e. the cold process stream) and E^Q the exergy supply stream (i.e. the hot utility stream). The output streams are referred to as E^{out}, (the sum of the heated process stream, E^{ut}, and the cooled utility/waste stream, E^a from the system under analysis) and I the inevitable exergy loss due to the irreversibility of the process.

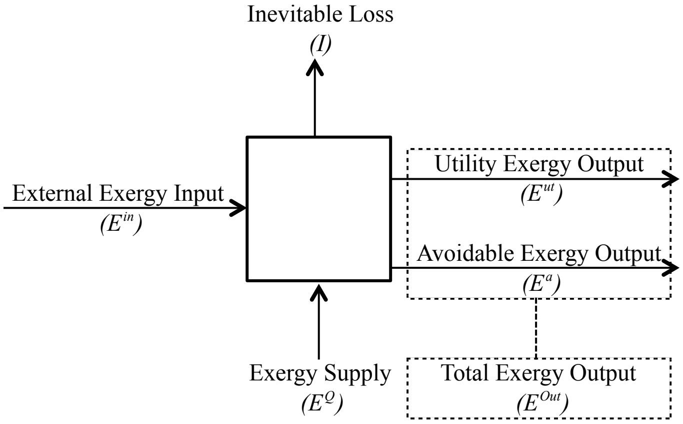

Figure 1: Individual process exergy balance

The exergy balance of any unit can be calculated as follows:

$$E^{in} + E^Q = E^{out} + I \qquad (3)$$

where

$$E^{out} = E^a + E^{ut} \qquad (4)$$

In Eq. (4) E^{ut} is the utility exergy for the process and E^a is the avoidable output exergy. Combining Eq. (3) and Eq. (4) it can be seen that there are only two potential variables - E^Q and E^a. The inevitable loss, I, is determined by the technology/equipment being used. The exergy of the input process stream, E^{in}, is determined by the parameters of the input process stream. The exergy of the heated output process stream, E^{ut}, is determined by the requirement of the process. Therefore it is only possible to change the value of the exergy supply, E^Q, by changing the value of E^a, i.e. a reduction in E^a will result in a reduction in E^Q. Alternatively E^{ut} and/or I must be changed through changes to the process or the technology. This last option is the most costly and is, in our method, considered the option of last resort. In existing facilities it is best to look first at what can be changed that will not result in alteration to technology or process.

Where there is more than one unit in the process to be optimized, the overall aim is to use waste heat from one unit as the input heat for another process. In terms of our model this means replacing E^Q with E^a from another process as much as possible. This will result in a simultaneous reduction of the exergy and energy demand and waste generation. The simplified approach proposed [10] operates to highlight in what way this might be achieved to best effect.

This simplified approach can be carried out for any unit once the scope and the boundaries of the unit under consideration are set. For example it could be used to look at and assess the performance of an entire production facility in a black box approach, to look at specific process streams within the facility, or to look at individual pieces of equipment. Once the stream data can be gathered then the assessment can be carried out.

When compared to a simple heat balance approach this system is of more benefit because it is an assessment of the performance of the system (through the calculation of I and E^a). In this case the exergy efficiency of the process can be expressed by the *External exergy performance factor (EExPF)* accounting for the overall losses – internal (inevitable) and external (avoidable):

$$\xi = \frac{E^{ut} - E^{in}}{E^Q} = 1 - \frac{I + E^a}{E^Q} \qquad (5)$$

This is an assessment of the work required by the system (E^{ut}-E^{in}) versus the work delivered to the system (E^Q). These “information points” have the potential to guide the engineer/researcher towards the key units for further investigation or analysis. In this way the engineer is prompted to scrutinise areas of the process or plant of maximum potential for improvement, without having to rely on specific knowledge of either the specific process or technology.

Combined method

The above discussion lays the foundation for the development of a General Approach to Low Grade Energy Management (GALGEM), based on the use of exergy analysis combined with existing process integration techniques [11, 12]. The simple exergy analysis takes place before any detailed process integration. This ensures that the engineer has enough information to determine the key areas with high potential, the areas of high waste and the effectiveness of the technologies. Therefore they will be in a better position to estimate the potential level of savings and the approach in terms of the most suitable Process Integration technique. The resultant proposed method, GALGEM, is as follows:

Step 1: Boundary definition – the boundaries of the system have to be defined at an early stage. The boundary can include outside waste streams or streams from another plant. Any part of the process or plant, as desired, can be included or excluded. Initially it is recommended to include as many streams as possible; these can easily be excluded at step 5.

Step 2: Data collection – flow-rates, temperatures, state, pressure, composition (if required), operating times (if applicable), stream identification name etc.

Step 3: Overall exergy analysis – It is recommended to do an overall exergy analysis of the entire system as defined in step 1. Carrying out an overall exergy analysis will initially give an overview of the performance of the system, and will enable easy comparison to the final proposed solution.

Step 4: Detailed exergy analysis – This analysis will be carried out individually on each item of plant/equipment, or if applicable input/output stream, being considered in the analysis.

Step 5: Elimination of infeasible options – based on the analysis carried out infeasible options can now be excluded. The reasons for infeasibility are to be determined on a case by case basis but typically will include reasons such as the waste stream having a low potential, difficultly in making changes in the considered area or a low potential return on investment (e.g. limited potential recovery from a highly corrosive stream)

Step 6: Tabulation of results – tabulation of the remaining options.

Step 7: Analysis of results – determination of the key areas for consideration, brief estimation of potential saving (using Exergy analysis) and determination of next step of analysis.

Step 7.1: Next step of analysis – Simple Process Integration / Pinch Analysis / HEN / Optimisation, etc.

Step 8: Proposed solution – detailed design of proposed solution.

Step 9: Analysis of proposed solution – using analysis as per Step 3 and/or 4 analyse the final proposed solution.

Heuristic Rules

The research team defined the heuristic rules to guide the process as follows:

1. Every output stream is a potential input stream.
2. Any changes in pressure, temperature or composition of a stream, within the system boundaries, must be included in the analyses.
3. Streams are to be used in order of their potential. The streams with highest potential are to be used first.
4. All streams are to be considered unless they are excluded due to infeasibility.
5. All options for heat recovery must be investigated before changes to the technology or process.
6. Where possible do not split streams as this can lead to increased cost.
7. All changes must lead to an improvement to either the overall exergy efficiency or a desirable improvement in the process.

CASE STUDY

The method was tested in an industrial case study. The test site is a large international semiconductor manufacturing plant. Heating and cooling is primarily provided to serve Air Handling Units (AHU) throughout the plant and for some heating and hot water circuits. Heat is also used in the Reverse Osmosis Deionised water (RODI) plant. There is no direct heating or cooling required for the process.

The site operates on a 24/7 regime, 363 days per annum. There are three 2.9 MW and one 1.45 MW natural gas fired boilers on site. The boilers are connected in parallel and the load is distributed simultaneously to all boilers. The temperature of the flue gases from the boilers is 179°C.

The average annual heat energy requirement, based on fuel consumption, measured is 22,300 MWh at Net Calorific Value (NCV), this corresponds to an average hourly fuel demand equivalent to a thermal power of 2.56 MW at NCV. This could in theory be covered by one of the 2.9 MW boilers. However in the presented work the major energy saving is at the expense of water vapour condensation from the flue gas. Therefore in the enthalpy balance the relevant Gross Calorific Value (GCV) is used, as this value reflects the total combustion energy content of the fuel. Based on the GCV of the fuel this would correspond to a thermal power requirement of 3.05 MW. The fuel specific exergy is assumed to 1.04 times the NCV [13] therefore the fuel exergy power (flux) is 2662 KW.

The heat is distributed throughout the site via a Medium Temperature Hot Water (MTHW) circuit. In the winter water is circulated out from the boiler plant at 110°C and returns at 95°C, while in the summer water is circulated out from the boiler plant at 100°C and returns at 80°C.

GALGEM Implementation

The steps in GALGEM were implemented in the case study as follows:

Step 1: Boundary definition – the analysis was restricted to all items of plant excluding the AHU. It follows that the analysis included the boilers, the MTHW circuit, the Hot Water Supply circuit (HWS), the RODI plant and the Radiator circuit (RAD). The environmental condition was set at the temperature of the cold water entering the site, i.e. 7°C. All calculations are based on the summer operating conditions.

Step 2: Data collection – basic data was collected from the site i.e. the temperatures, flow-rates and operation schedules of the included streams, as defined in step 1.

Step 3: Overall exergy analysis – this was carried out in a very basic manner using data gathered from the boiler operation. As the system is a closed loop the only output streams were the boiler flue gas and uncontrolled operational losses.

Step 4: Detailed exergy analysis was carried out on the individual units, the RODI plant, the HWS circuit and the RAD circuit. Although named “detailed” this was a relatively simple process involving the data collected and steam table information.

Step 5: Elimination of infeasible options: no infeasible options were found.

Step 6: Tabulation of results – see Table 1 and Figure 2.

Step 7: Analysis of Initial Results – It is clear that the exergy generated in the overall system is used to supply the E^{ut} and I of the MTHW circuit. The MTHW circuit then distributes the exergy throughout the plant to the various exergy sinks. (Note: the AHU exergy balances are not included in the individual unit analysis, but are an integrated part of the MTHW circuit analysis. For the purpose of our analysis the AHUs are considered to be a fixed load that will not change in any way.)

From analysis of the individual units it is revealed that exergy is lost due to E^{ut} and I in all of the units. It is also clear that the avoidable exergy E^a generated is high in these units. However as the system is a closed system the avoidable exergy E^a streams are all returned to the boiler. In the case of the RODI plant E^a represents an additional exergy loss. This is because the temperature of E^a for the RODI plant is below that of the final water returned to the boiler (80°C) and requires heating to reach the return stream temperature. This amounts to an exergy demand of 16.4kW to the MTHW (see Figure 2).

The individual units are already in accord with the first heuristic rule of GALGEM i.e. the output streams E^a in the individual units are themselves input streams. The next heuristic rule is that the streams should be targeted in order of their potential (i.e. exergy value). In the presented case study this would mean trying to find alternative sources for the sinks in the following order: (i) the MTHW circuit; (ii) RAD circuit; (iii) HWS; (iv) RODI plant. The third heuristic rule is that all streams are to be considered. In this case study the streams are limited and only one stream in the system identified as a potential alternative heat source to the MTHW system. This is the flue gas from the boilers. As part of a parallel study carried out on this site the potential for waste heat recovery from the flue gas was assessed [14]. The proposed system involves the installation of a combination of technologies, an indirect heat exchanger and a second-generation contact economiser, to capture the waste heat in the flue gas. Adopting the proposed system may appear to be in contradiction with heuristic rule No. 4, however this is not the case as it has been established that there are no other options for heat recovery.

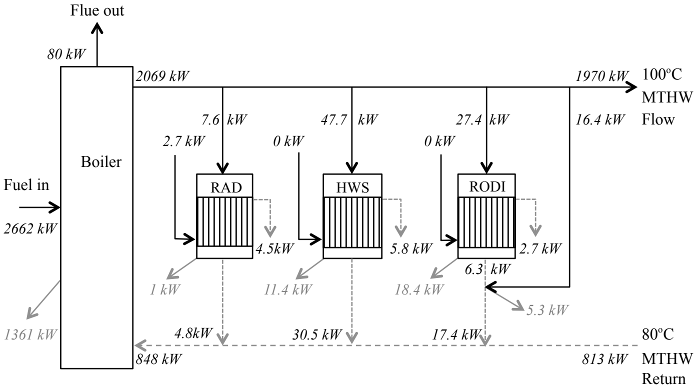

Figure 2: Initial system exergy analysis diagram

Individual unit exergy analysis	E^{in}	E^{Q}	E^{ut}	I	E^{a}
	kW	kW	kW	kW	kW
RAD circuit	2.7	7.6	4.5	1.0	4.8*
HWS	0.0	47.7	5.8	11.4	30.5*
RODI	0.0	27.4	2.7	18.4	6.3**
RODI input to MTHW	6.3	16.4***	17.4	5.3	
MTHW circuit	0.0	1970	1157		813
Overall system	**0.0**	**2069**	**1221**		**848**
Boiler	**848**	**2662**	**2069**	**1361**	**80.0**

* E^a is reused as an input in the boiler return.

** E^a is reused as an input in the boiler return; it requires additional E^Q to reach the temperature of the boiler input stream.

*** Above mentioned additional E^Q, supplied by the boiler.

Table 1: Initial exergy analysis data

Step 7a: As this is a relatively simple system with no simultaneous cooling occurring and with only one alternative heat source, the research team decided that simple process integration was sufficient.

Step 8: Proposed solution – the proposed solution is to use waste het recovered from the flue gas via an indirect heat exchanger and a second-generation contact economiser to replace heat currently supplied by the boiler. This will involve the installation of an indirect heat exchanger, and a second-generation contact economiser system on the boiler flue, and the installation of two new plate heat exchangers. The installation of associated control and monitoring systems will also be required.

Step 9: Analysis of the proposed solution – Table 2 gives the exergy values of the proposed solution (Figure 3).
Here the boiler is considered together with the Heat Recovery System (HRS) as an integrated exergy supply unit with two output streams – hot water and flue gas. Internal exergy circuits inside of this unit, i.e. the exergy exchange, the inevitable losses and the combustion air prehumidification and preheating at the indirect and direct contact heat recovery, are not considered separately. The impact reflects the overall parameters only. The detailed internal exergy analysis of this unit is the focus of another paper under preparation.

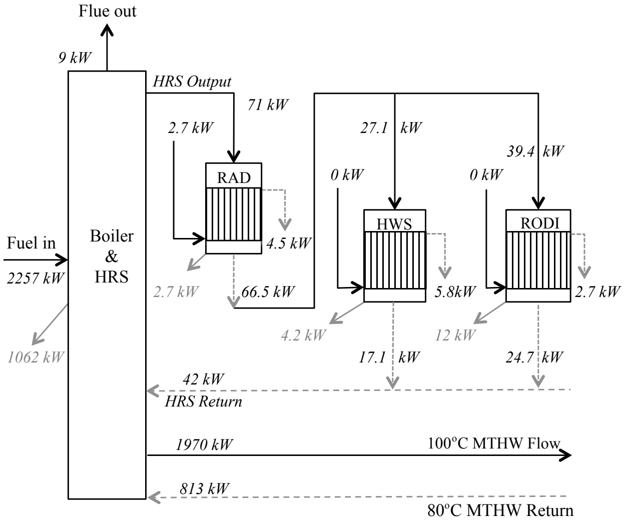

Figure 3: Proposed solution exergy analysis diagram

Individual unit exergy analysis	E^{in}	E^{Q}	E^{ut}	I	E^{a}
	kW	kW	kW	kW	kW
RAD circuit	2.7	71	4.5	2.7	66.5*
HWS	0.0	27.1*	5.8	4.2	17.1
RODI	0.0	39.4*	2.7	12.0	24.7
RODI input to MTHW	0,0	0.0	0.0	0.0	
MTHW circuit	0.0	1970	1157		813
Overall system	**0.0**	**2041**	**1186**		**855**
Boiler & HRS	**855**	**2257**	**2041**	**1062**	**9**

* Linked values - *(E^a)* is reused to supply *(E^Q)*

Table 2: Exergy values of proposed solution

From the comparison between Table 1 and 2 it can be seen that the individual units E^{ut} requirements do not change, There are less inevitable losses in the new case. However these exergy losses are now fulfilled through heat recovered from a previously wasted stream, the flue gas. The parameters of the MTHW circuit remain the same because it is not affected by the HRS. It can be seen (Figure 3) that in the new case there is no longer a cool stream input from the RODI plant to the MTHW circuit, so this exergy loss is also removed. As a result the Overall system exergy supply slightly decreases. The efficiency improvement comes from heat recovery and reuse from the flue gas. It is demonstrated by comparing the parameters of the (Boiler + HRS) integrated exergy supply unit before the heat recovery and after. The avoidable loss E^a is reduced dramatically - from 80 to 9 kW; the inevitable loss is reduced by 20% and the fuel exergy demand is with 15.2% lower. The External Exergy Performance Factor, according to the Eq. (5) increases from 45.9% to 52.5% in the new case. In Table 3 the overall heat saving and its breakdown according to the sources are given.

Process	Power, kW	Saving, %
HWS	12	0.6
RODI	75	3.4
Radiators	109	5.0
MTHW	98	4.5
Combustion air preheating	37	1.7
Overall Fuel Saving	**331**	**15.2**

Table 3: Heat saving in the proposed solution

Table 3 shows the savings achieved across all of the streams under consideration. It is important to note that for the heat recovery system to be viable there is no one heating stream that can be matched directly with the source (i.e. the flue gas). Instead the processes have been integrated to ensure the maximum saving is achieved for both the individual streams and the overall system. It is also to be noted that drop in demand on the boiler, as a result of the proposed measures, can lead to additional savings, such as reduced maintenance, reduction in requirement for supplementary boiler, reduced standby boiler requirement etc.

CONCLUSIONS

This paper has shown a relatively simple approach to process analysis for low-grade energy management, called GALGEM. It has outlined the steps in the process along with the heuristic rules for guidance. From the case study it is clear that the system can work to guide the designer or engineer towards increased energy efficiency through the management of waste heat. The potential savings have been demonstrated. Importantly the case study shows how through the simplified approach it was relatively clear what level of analysis was required, prior to carrying out any detailed study. I.e. in this particular case, once the boundaries had been established and some initial calculations carried out it was clear that there were a limited number of streams for analysis, thus no complex process integration was required.

In conclusion it is demonstrated that the proposed approach offers a simplified method by which to carry out heat energy assessment.

ACKNOWLEDGEMENTS

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