Modelling of a CHP System with Electrical and Thermal Storage

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***Abstract*—Decentralised energy generation is increasing in popularity because it provides for higher efficiencies and is consequently more environment friendly than the current centralised solutions. Most of the inefficiencies of centralised power stations lie in the large amount of waste heat. This is largely overcome when using Combined Heat and Power systems where the heat as well as the electrical output is used, but these outputs are generally constant, while any demand would be continuously fluctuating. The only way to deal with this imbalance between supply and demand is through the use of energy storage, and therefore this paper investigates the benefits of combining energy storage systems with a CHP system to determine the potential efficiency improvements from such a combination. A full model of this system, which consisted of several sub-models to deal with the various elements of energy generation and storage was developed in Matlab/Simulink and used for simulation using some real-life demand data. The results show that through the addition of correctly sized thermal and electrical storage to a CHP system, the CHP system is able to run continuously at optimal efficiency.**

***Index Terms*—CHP; Electrical Storage; Internal Combustion Engine; Thermal Storage;**

I. Introduction

The move towards a reduction of greenhouse gas emissions, has led to an increased focus towards improving efficiency. Consequently, decentralized renewable generation is being promoted, especially when this consists of bio-fuelled Combined Heat and Power (CHP) systems. A CHP system can benefit from a reduction in fuel consumption of about 35% versus the use of conventional energy supply mechanisms [1]. However, CHP systems would generally still suffer from losses if the demand is lower than the supply, and may at times not be able to fully support the demand. The balance between user demand and supply has been a long standing challenge in the context of energy generation, because of the fact that the ever changing demand profile makes it quite complex to match supply to demand. It is well known that energy storage buffers can help to deal with such differences between supply and demand, and while current CHP systems may get fitted with a thermal store, they rarely get fitted with electrical storage, even though that can also bring specific benefits. The addition of these energy storage facilities, will not only improve the flexibility of a CHP system and its overall efficiency, but such an uncoupling between production and demand allows for energy not needed at production time to be stored and used when extra energy is required, while excess electricity could e.g. even be sold to the grid when profit margins are more optimal [2].

Research carried out by [3] has shown that the commercially available CHP technologies are; Reciprocating Internal Combustion Engine (ICE) based systems, micro-gas turbine based systems, fuel cell based systems and external Stirling engine based systems. According to [3] & [4], ICE based systems have electrical efficiencies ranging from 35 to 45% and overall efficiencies of 85-90%. On the other hand, micro-gas turbine based systems have overall efficiencies of about 80% while having low maintenance costs. On the other hand, fuel cell based systems are still more of an emerging technology, they are still being studied to obtain accurate performance data. For example Panasonic in conjunction with Tokyo gas developed a $1kW_e$ output and $1.3kW_{th}$ output PEM fuel cell based CHP unit, which is being field trialled in Japan [5]. So far, it has been shown that fuel cell based systems have an efficiency of about 65 to 75%, with low noise level. However, their high cost and short lifespan are a major drawback. Finally, Stirling engine based systems are being reintroduced into the market due to technological improvements and their potential to hugely reduce emissions. The electrical efficiency of such Stirling based systems is typically about 40% with an overall efficiency of 65-85%.

Quite often, thermal storage is added to a CHP system to allow for the excess in heat produced to be stored for later use [6]. A good thermal storage should ensure that the stored heat is not expelled into the environment, which requires good insulation. Similarly, one can decide to store electrical energy in various ways. The requirement for storing and using heat and electrical energy does not solely apply in a CHP context, but also applies to any renewable energy generation method, making energy storage invaluable to the balance between user demand and supply.

Therefore this paper investigates the benefits of adding thermal and electrical storage to a CHP system through sim-

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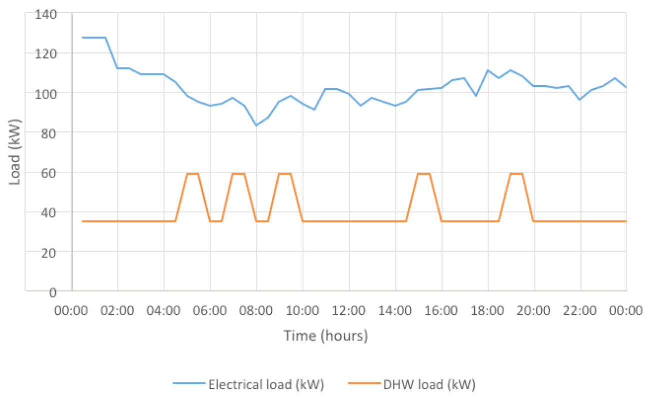

Fig. 1. Electrical and Thermal load profile

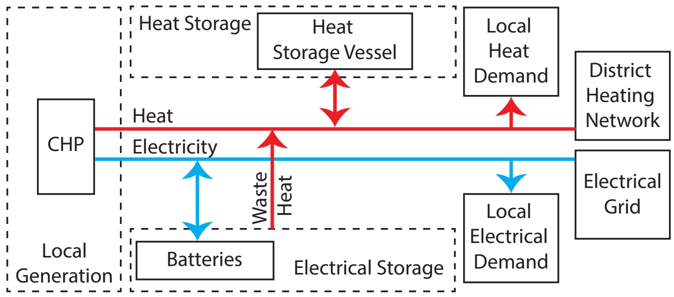

Fig. 2. Block Diagram of a CHP System with Thermal and Electrical Storage

ulation, for which Matlab/Simulink was used. The designed simulation model is described and simulated, after the results are discussed and the paper concluded.

II. Proposed Design

The CHP system used in this paper is of the ICE-type, while the user's demand profile is based on real data as shown in Figure 1.

Due to the required system and sub-elements to be modelled, Simulink was identified as the most suitable modelling environment. Through its various add-on environments the full system, as shown in Figure 2 was developed as sub-models. Unfortunately, the simulator did not allow for all sub-models to be combined directly, in which case the sub-models were linked through the use of input/output data. These sub-models created, were: 1) Internal Combustion Engine (ICE) with generator, 2) electrical and 3) thermal storage system.

A. Internal Combustion Engine with Generator

An Internal Combustion Engine model is used to represent the CHP energy generation system, since it is among the most popular CHP technologies, allowing the model to represent the most realistic set-up. The engine model is based on data supplied by manufacturers which ensures a good prediction of the actual system performance. It is assumed that the ICE is not modulated and therefore the electrical output would be constant while the user load varies per hour [7]. Consequently, there is a need for interaction between the ICE and the battery storage, whereby any excess or extra electricity is stored in or supplied by the battery respectively. The assumption of a constant electrical output also results in the need to properly size/select the CHP system and storage capacities for a given environment. Essentially that means that one should aim to operate the ICE at minimum fuel consumption point, which results in maximum electrical efficiency of the system. In this specific simulation the ICE setup is linked to an AC generator to complete the CHP system, which provides for $105kW$ electrical, while the engine produces $47kW$ thermal output. The low thermal output is due to the fact that only cooling liquid is used, and exhaust heat is not extracted. As load to the system an RLC load block was used, while load changes were implemented through the use of a three-phase circuit breaker combined with different RLC loads.

B. Electrical storage

Any electrical energy, which is not of benefit to the actual load itself, would be automatically stored into electrical storage, while any deficit in electricity would be topped up by storage. The chosen electrical storage technology in this model was battery storage due to its high energy and power density. However, for large energy storage requirements, batteries may not necessarily be the best solution. For this simulation, a lead acid battery model was used which includes state of charge characteristics, and therefore allows for accurate simulations over longer periods of time. The model makes use of data supplied by battery manufacturers which makes it a realistic model. Considering that batteries normally operate on DC, while the generator and load are AC, a rectifier and inverter are introduced to deal with the necessary conversions. The battery and power converter circuits are large circuits to implement which increases the complexity of the entire system, but Matlab has a block called: Universal Bridge which can be used as rectifier and inverter. The appropriate option of power electronics had to be selected to adapt the universal bridge for this specific application. The power converter components are added in with the electrical storage sub-model. This electrical sub-model was then combined with the ICE model in order to test the electrical storage efficiency. This combined model is shown in Figure 3, which uses the diesel engine scope to display the engine output characteristics.

C. Thermal storage

The sub-model for thermal storage was built around the hot water storage tank model developed by G. Rouleau [8], which uses water as the storage medium because it is easily accessible, and one can cheaply store water at high temperatures in pressurized tanks [9].

The thermal demand in this case is limited to the users hot water, and so it ignores the space heating requirement, which is on average larger. Secondly, the heat supply only comes from the engine's cooling, which is generally of lower temperature than the heat recovered from the exhaust gases. The main design requirement for the thermal storage is for

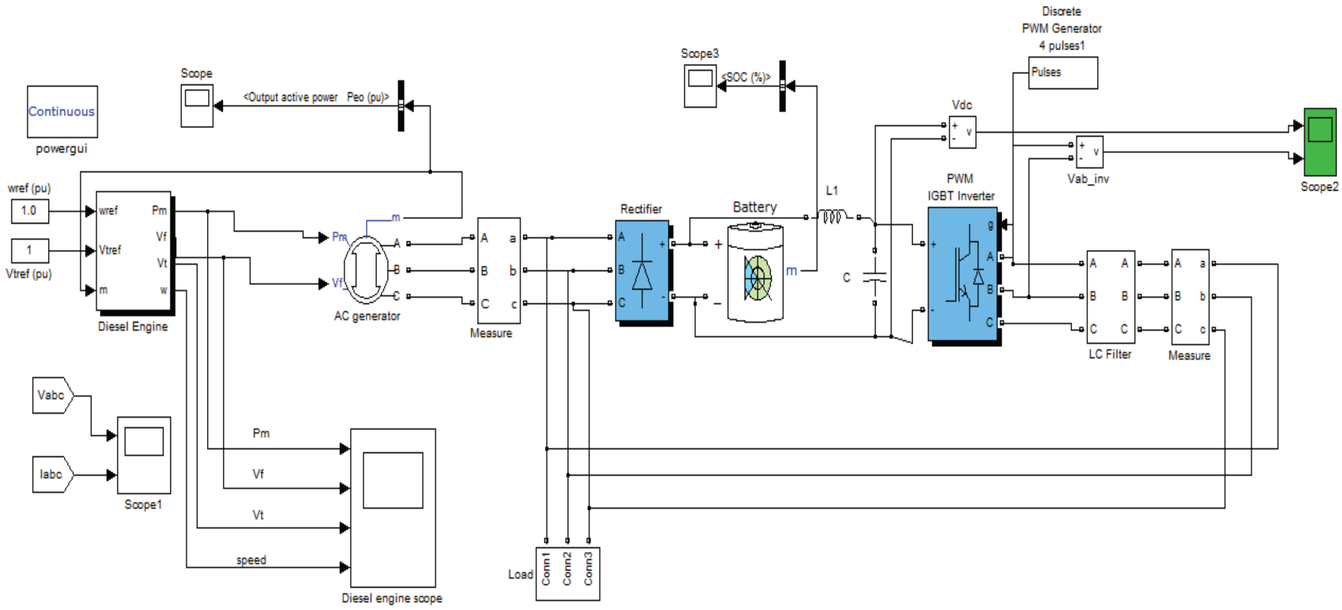

Fig. 3. Developed Model of CHP System with Electrical Storage

it to be able to minimize the dumping of waste heat. This is achieved by retrieving heat from the diesel engine cooling through a heat exchanger, which deals with the heat exchange between the different media. The heat exchanger heats up the water in the storage tank which fulfils the users hot water demands. The model also takes into account any heat loss from the tank through convection and conduction and these are modelled using the appropriate components.

III. Results & Discussion

After developing the various sub-models, they were combined either directly or indirectly through the input/output of data. In order to complete the system, the size of the individual components of the system still needs to be specified. This can be achieved by looking at the differences between demand and supply over a fixed period of time. Obviously the longer this period the better the design would be, but one has to also ensure some extra capacity since demand profiles can vary due to e.g. weather conditions, user habits and so on. An energy balance chart showing the electrical energy storage requirements on an hourly basis is shown in Figure 4. The figure shows that the maximum difference between supply and demand at any point in time is $20kW$, one then needs to take additional account of the time over which the excess and shortage of supply cancel one another out to determine the overall kWh storage capacity needed. From the larger system's set-up, one also needs to take factors such as the CHP production, the willingness to sell electricity to the grid and so on into account. As one will appreciate this becomes a rather complicated design question, which was not the main aim of this study.

Due to the use of battery storage, a universal bridge that is used as rectified and inverter was introduced. The results of which are shown in Figure 5 where the first trace shows the DC voltage output from the rectifier used to charge the battery. The output has been zoomed into in order to capture the ripple of the DC, which has a maximum value of 20V and an average value of 430V. In order to reduce this ripple, the filter values could be further increased. The second trace shows how the DC voltage from the battery has been inverted to AC voltage which is used by the load. The AC voltage is also zoomed. The average value is 400V showing a small power loss due to the conversion. However, the use of this universal bridge reduces the complexity of the overall model considerably, because it automatically deals with either storing into the batteries or taking energy from storage when required. From the users demand profile and the system output, the CHP system supplies about 85% of the load, which means the battery supplies the remaining load. From the results, it can be seen that the addition of the battery to the CHP system reduces the need to use a larger CHP unit which reduces the amount of wasted power. This reduction in waste then also means that the CHP system can operate at minimum fuel point, resulting in a higher operating efficiency and reduced cost.

The thermal sub-model was modelled and simulated separately from the CHP system with battery storage. This is because the two Simulink/Matlab add-on environments used to model the different sub-models cannot be combined as some component blocks are not compatible. To identify the required storage capacity for the thermal storage, one can create a thermal energy balance, as shown in Figure 6. This balance again indicates the required storage to deal with the fluctuations in supply and demand, which in this case is 12kW, while the time factor needs to be included when determining

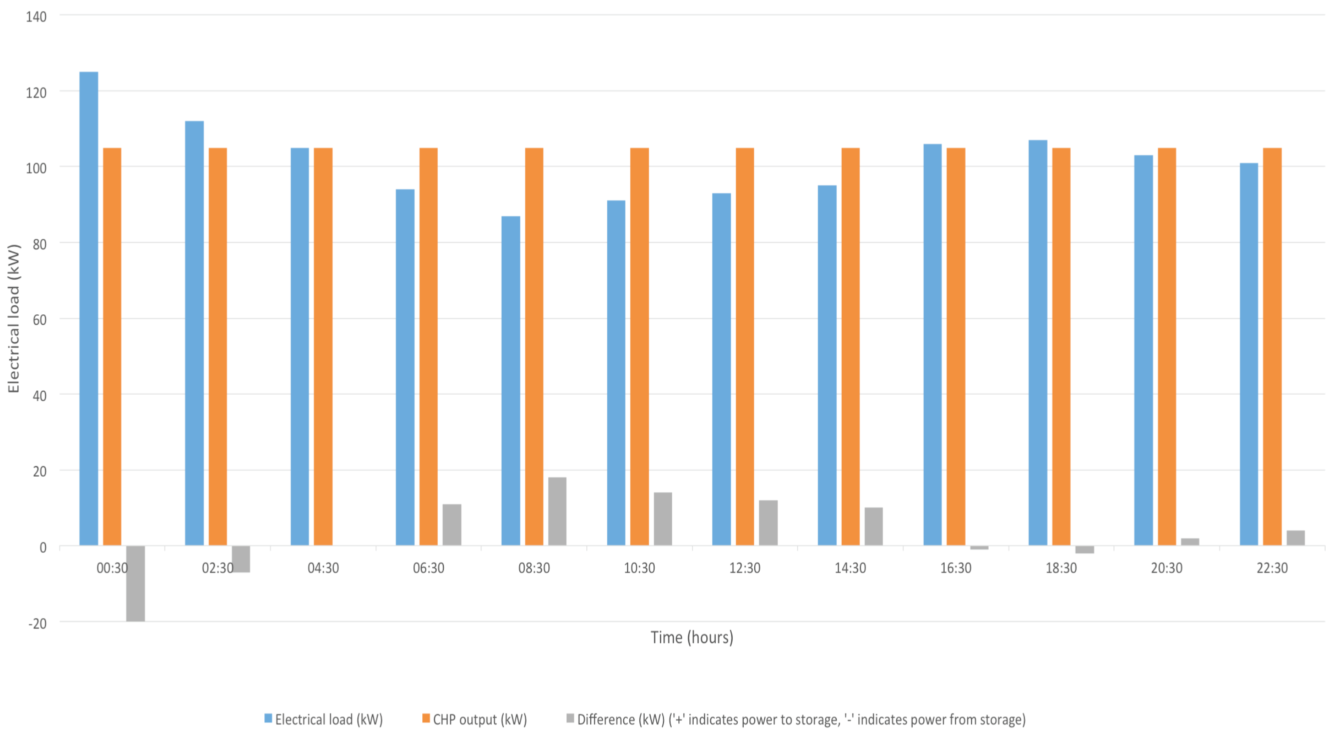

Fig. 4. Hourly Electrical Energy Balance for CHP + Storage model

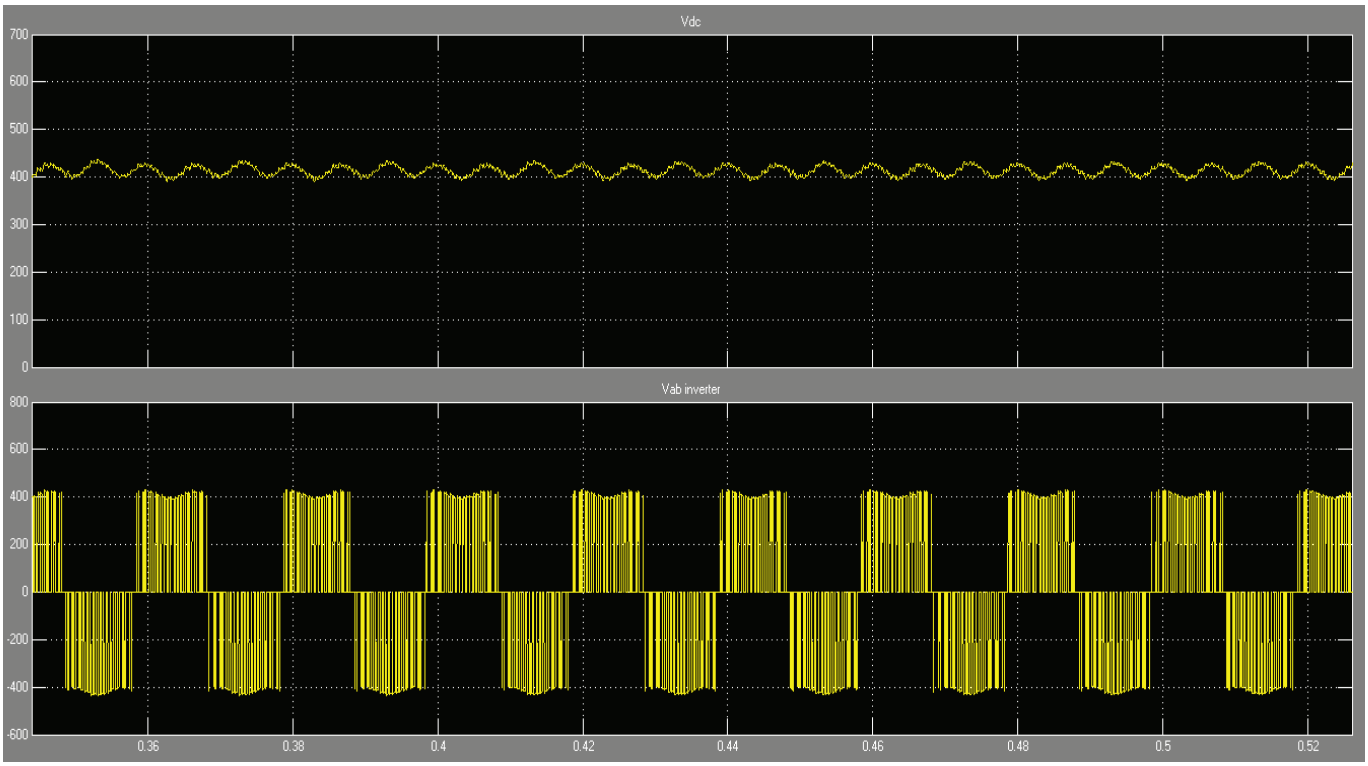

Fig. 5. Rectifier and Inverter Output Voltages

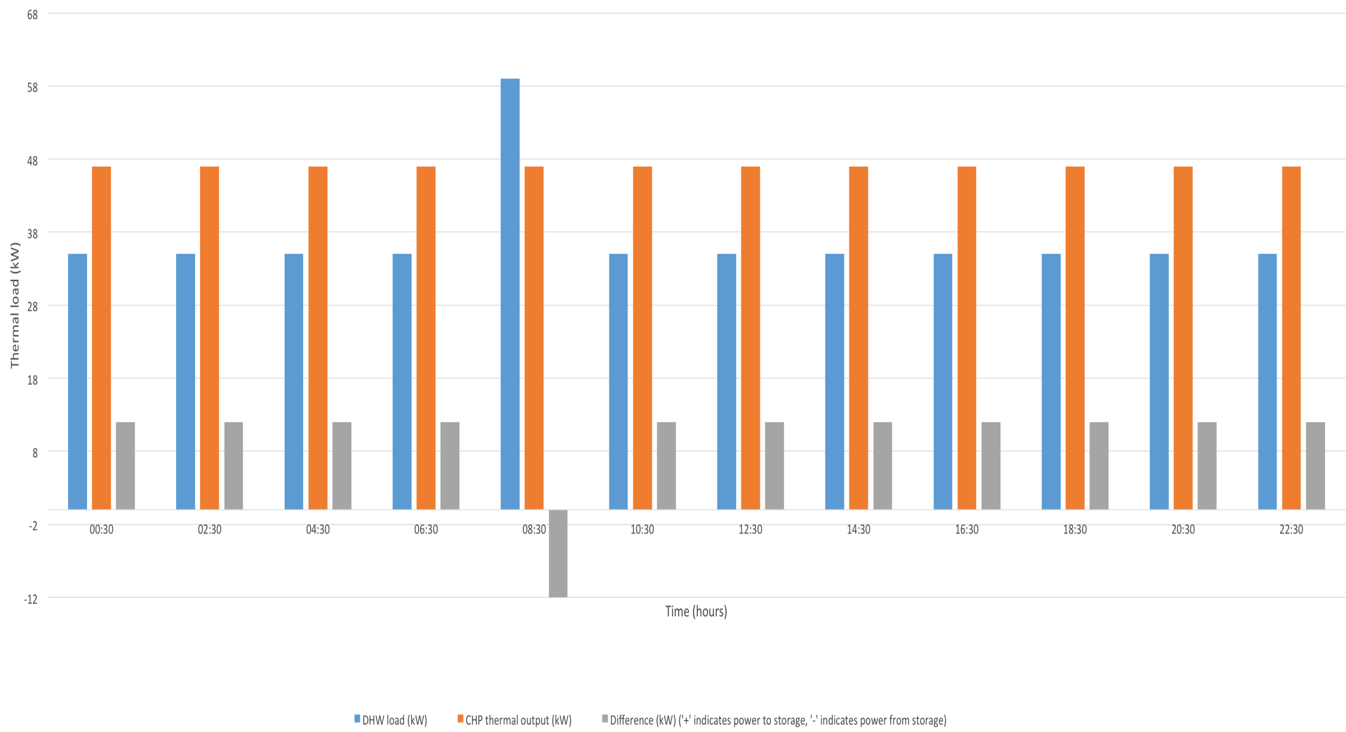

Fig. 6. Hourly Thermal Energy Balance for CHP + Storage model

total storage capacity. By being able to store the required excess heat for use at a later point in time, one ensures that there is effectively no waste and the CHP runs at optimal efficiency since all outputs are used/stored.

The results show that through the addition of correctly sized thermal and electrical storage to a CHP system, the CHP system is able to run continuously at optimal efficiency. The efficiency of a system without storage depends on the amount of energy that is wasted, and could therefore be continuously changing, not to mention that one needs extra energy sources to fulfil demand when it is larger than the CHP output. Therefore, a properly sized storage system can actually allow for the CHP system size to be reduced and improve on cost, maintenance, and emissions.

IV. Conclusion

In this work, a model of a CHP system with both electrical and thermal storage was developed using Matlab/Simulink. The model was first of all developed, and then analysis was done on the model to determine the effect of storage on overall system efficiency. Through the addition of a battery of 20kW capacity and a hot water storage tank of 12kW, the efficiency of the CHP system can continuously be kept at its maximum, which stands in contrast with the normal cases where as soon as supply and demand are different there is an energy shortage or waste. One could even decide to buffer e.g. electrical energy to sell it off when profit margins are highest and therefore make profit from energy that would otherwise have been wasted.

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