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POWER MANAGEMENT CONTROLLER FOR HYBRID ELECTRIC VEHICLE USING FUZZY LOGIC

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ABSTRACT

This paper presenting a study on hybrid electric vehicle (HEV), using backward facing approach simulation or QSS approach and fuzzy logic power management controller for HEV. The software being used for modelling of HEV and fuzzy logic power management controller is MATLAB/Simulink. A comparison study was completed to investigate fuzzy logic power management controller capability compared to optimal ideal controller optimized by dynamic programming. It was concluded that fuzzy logic controller shows excellent performance as HEV final battery SOC lies within 2.8% margin of that dynamic programming. Then, a comparison study was completed after addition of supercapacitor set to this HEV against battery only supply. After fuzzy logic PMC modified to include supercapacitors addition, it was observed that fuel economy improved by 54.34% from 57.6 mpg to 88.9 mpg, and total energy consumption reduced by 27.27%.

Keywords: hybrid electric vehicle, HEV, EV, supercapacitor, power management controller, quasi-static simulation, QSS.

INTRODUCTION

Over recent years, the threat of global warming and water-energy nexus issue had alerted many developed nations on the importance to reduce fossil fuel consumption. These also encouraged and urged researchers to find alternative solution in response to this issue; especially in automotive technology which had shifted course towards higher fuel economy operation in effort to reduce the threat of global warming and energy-water nexus issue. Among few well-known technologies are hybrid electric vehicles (HEV) and full electric vehicle (FEV) such as Toyota Prius and Tesla Model S respectively.

Many researchers are working on to improve those fuel saving vehicle technologies; including downsizing of internal combustion engine, implementation of energy recovery system, addition of super-capacitors and implementation of effective power management controller. Thus, a power management controller within a HEV vehicle is indispensable; with purpose of setting the most appropriate power flow from electric motor and internal combustion engine, also power flow from either battery or supercapacitor. The most appropriate power flow determined by the controller will increase fuel economy of HEV. This paper will emphasize on power management controller developed using Fuzzy logic method to achieve high fuel economy close to optimal ideal.

Moreover, effects of supercapacitors addition to HEV fuel economy improvement are also investigated in this work, based on its usage during high power demand and regenerative braking. Supercapacitor are known to be a bit pricier than battery, but has excellent characteristics including high charge/discharge cycle, high power density and high power charge/discharge limit which makes it excellent for acceleration and braking in HEV.

Among power management controller (PMC) types for HEV are heuristic, predictive controller and offline optimization. Heuristic method includes Boolean logic and fuzzy logic method. PMC built based on Boolean logic are simpler and allow designer intuitions to be implemented, but it may reduce fuel saving potential if many variables included. Also, it relies heavily on designer's intuition means many unforeseeable operating conditions which also contributed to lower fuel savings.

Then, there is fuzzy logic, which based on degrees of truth (0 to 1) rather than absolute binary logic (0 and 1). Despite many method of power management controller available recently, fuzzy controller remains competitive due to its good reasoning capability. Moreover, it's implementable as real time strategies because of its simplicity and quick decision making process. A HEV fuzzy based controller optimized using Particle Swarm Optimization (PSO) shown improvement about 5% to 10% over fuzzy controller without optimization [8]. Furthermore, optimization using Genetic Algorithm (GA) method showed improvement of about 4.8% [3]. These show effectiveness of fuzzy controller, although it's not optimal, it's very close to optimal. A fuzzy control strategy for regenerative braking system in electric vehicle (EV) presented in [10], the controller shows significant improvement over initial vehicle model in energy recuperated and regenerative braking efficiency; 867 kJ compared to 311 kJ and 86% compared to 44.6%.

Meanwhile, predictive controller such as model predictive controller (MPC) and equivalent consumption minimization strategy (ECMS) also shows high fuel economy potential. It based on prediction of future power requirement predicted on-board of HEV. Although this method allows real time implementation, it requires knowledge of future terrain (road grade, traffic lights, etc.), which is a problem because GPS device are not available to all HEV due to its higher price tag.

An offline optimization strategy that shall be mentioned here is Dynamic Programming (DP) optimization method, which integrated into power management controller, and claimed to be the best for benchmarking purpose [1]. This method shows

improvement over Equivalent Consumption Minimization Strategy (ECMS) method for approximately 5-10% of fuel economy. However, its complexity and high computational burden remains major obstacles for real time implementation.

The addition of super-capacitor units proved to be a feasible and effective to provide additional torque or power requirement in hybrid vehicle powertrain system [7]. The engine compared is 3.0 litres naturally aspirated and 1.8 litres turbocharged (downsized). The result presented in that paper proved that the supercapacitors torque booster system capable of providing 140 Nm of required additional torque during turbo lag moment (RPM<3000). Moreover, the energy consumed during acceleration period can be fully recovered during regenerative braking moment which is approximately around 150 kJ. In an experimental study, supercapacitors proved to improve regenerative braking efficiency up to 88% [11]. Also, supercapacitors showed fuel economy improvement by 5.79% [9]. These reports supported that supercapacitors addition is a promising modification in HEV to achieve higher fuel economy.

Moreover, supercapacitor and battery as combined electrical energy storage controlled through fuzzy logic controller showed improvement of acceleration time from 13.2s to 12.1s and fuel consumption from 8.1 l/100km to 7.2 l/km [5]. Thus, fuzzy logic controller is proven excellent for HEV power split between ICE and EM. Also for combined power supply (battery & supercapacitor) management as mentioned recently. Thus, it is selected as implementable effective power management controller for achieving high fuel economy in HEV for this study.

METHODOLOGY

HEV model is built in MATLAB/Simulink environment for investigation of fuel economy. Instead of building dynamics model which is forward facing approach, the HEV model will be built using quasi-static method which is backward facing approach. The QSS toolbox can be run in MATLAB/Simulink software. Despite simplicity of QSS toolbox, its accuracy lies within 1% compared to that dynamic approach [1]. The vehicle model in this study is a generic HEV [1]. Vehicle specifications are summarized as in Table-1.

Fuzzy controller is also a built-in function in MATLAB which uses several inputs and membership functions to determine outputs. In HEV model built, this PMC will require input including power requested from transmission (P_MGB), rate of power requested from transmission (P_MGB/dt), battery state of charge (B_SOC), Supercapacitor state of charge (SC_SOC), charging logic initial signal (CL(i)), and charging logic final signal (CL(e)). Fuzzy controller output are 3 variables including hybrid ratio (HR), split ratio (SR), and auxiliary switch (A). This HEV operating modes are shown in T able-2. Fuzzy PMC input, output variables, and their membership functions are summarized as shown in Table-3.

Table-1. Generic diesel parallel HEV specifications.

Nominal engine power	150kW
Minimum engine speed	105 rad/s
Maximum engine speed	628 rad/s
Nominal motor power	40 kW
Maximum motor speed	628 rad/s
Maximum battery capacity	7.64 Ah
Nominal open circuit voltage	263 V
Maximum battery current	200 A
Supercapacitor capacity	40F x 10 (Parallel)

For power requested from transmission (P_MGB), its membership functions are defined into 5 which are negative (N), auxiliary power (Aup), low power (LP), medium power (MP), high power (HP). For rate of power requested from transmission (P_MGB/dt), its membership functions are defined into 2 which are low (L) and high (H). For battery state of charge (B_SOC) and supercapacitor state of charge (SC_SOC), its membership functions are defined into 3 which are low (L), medium (M), high (H). For charging logic initial signal (CL(i)), its membership functions are defined into 2 which are charging on period (I), and charging off period (O). For charging logic final signal (CL(e)), its membership functions are defined into 2 which are charging (I), and not charging (O). For hybrid ratio (HR) output, its membership functions are defined into 3 which are engine only (E), hybrid mode (HM), and electric only (I). For split ratio (SR) output, its membership functions are defined into 2 which are battery (B) and supercapacitor (S). For auxiliary switch (S) output, its membership functions are defined into binary logic which is auxiliary on (1), and auxiliary off (0). An overview of fuzzy controller surface map and rules are shown in figure-1, and the box diagram representing HEV model with Fuzzy logic PMC shown in Figure-2.

On second issue, the addition of supercapacitors to the HEV model to investigate its impacts on fuel economy. It based on equation shown below [4], valid for both charging mode and discharging mode:

$$\text{Supercapacitor voltage; } U_{sc} = \frac{1}{C_{sc}} . Q_{sc} \quad (1)$$

Where, Supercapacitor charge is integration of current ($\dot{Q}_{sc} = I_{sc}$);

$$I_{sc} = \left(\frac{-Q_{sc}}{C_{sc}} \pm \sqrt{\left(\frac{Q_{sc}}{C_{sc}}\right)^2 + 4.P.R_{sc}} \right) / (2.R_{sc}) \quad (2)$$

The supercapacitor model will be added to the HEV model in parallel to battery, and controlled by modified Fuzzy PMC which includes supercapacitor SOC as an input. As depicted in Figure-2, this setup enabled investigation of fuel economy after the addition.

In order to compare between combined power supply or CPS (supercapacitors and battery) and battery only supply or BS, one method is introduced here. This is called; total energy consumed by HEV, which constituted of fuel energy and electrical energy. Fuel energy can be estimated by equations shown below.

$$E_f = m_f \times HV_f \tag{3}$$

Where; E_f is fuel energy, m_f is mass of fuel, HV_f is fuel heating value (Diesel heating value: 45 MJ/kg).

Table-2. Operating modes of HEV in study.

No.	P_MGB	Mode	HR	P_ICE	P_EM	P_BT	P_SC
1	+	Car Stop	0	0	0	0	0
2	+	ICE only traction	0	>0	0	0	0
3	+	EM only traction	1	0	>0	>0	0
4	+	EM only traction + SC Boost	1	0	>0	>0	>0
5	+	Hybrid traction	0<u<1	>0	>0	>0	0
6	+	Hybrid traction + SC Boost	0<u<1	>0	>0	>0	>0
7	+	ICE only traction + Battery charging	0	>0	<0	<0	0
8	-	Regenerative braking	1	0	<0	0	<0
9	-	Regenerative braking + Battery charging	0	0	<0	0	<0
10	+	Deceleration to constant speed	1	0	<0	<0@0	<0@0

Table-3. Variables and membership functions for fuzzy logic PMC.

Mode	P_MGB	P_MGB/dt	B_SOC	SC_SOC	CL (e)	CL(i)	HR (u)	SR (q)
1	0	0	All	All	O	-	E	-
3	AuP	-	L	All	All	-	I	B
			M	All	All	-	I	B
			H	All	O	-	I	B
	LP	L	M	All	O	O	I	B
			H	All	O	-	I	B
	MP	L	M	All	O	O	I	B
			H	All	O	-	I	B
4	LP	H	Not L	M	O	-	I	S
				H	O	-	I	S
5	HP	L	M	All	O	O	M	B
			H	All	O	-	M	B
6	MP	H	Not L	M	O	-	M	S
				H	O	-	M	S
	HP	H	Not L	M	O	-	M	S
				H	O	-	M	S
8	N	-	All	L	O	-	I	S
				M	O	-	I	S
				H	O	-	I	S (A=1)

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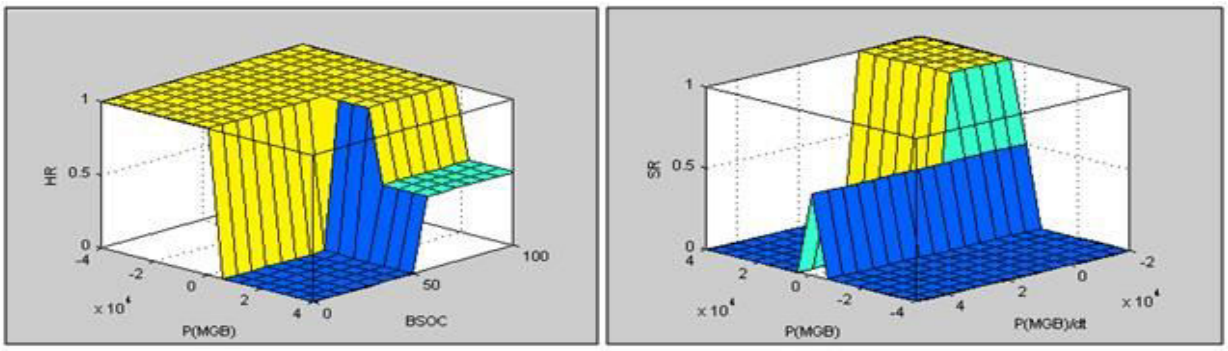

46. If (P(MGB) is LP) and (P(MGB)/dt is N) and (BSOC is M) and (CL(e) is O) and (CL(i) is O) then (HR is I)(S
47. If (P(MGB) is LP) and (P(MGB)/dt is N) and (BSOC is M) and (CL(e) is O) and (CL(i) is I) then (HR is E) (1
48. If (P(MGB) is MP) and (P(MGB)/dt is N) and (BSOC is M) and (CL(e) is O) and (CL(i) is O) then (HR is I)(S
49. If (P(MGB) is MP) and (P(MGB)/dt is N) and (BSOC is M) and (CL(e) is O) and (CL(i) is I) then (HR is E) (1
50. If (P(MGB) is HP) and (P(MGB)/dt is N) and (BSOC is M) and (CL(e) is O) and (CL(i) is O) then (HR is HM
51. If (P(MGB) is HP) and (P(MGB)/dt is N) and (BSOC is M) and (CL(e) is O) and (CL(i) is I) then (HR is E) (1
52. If (P(MGB) is LP) and (P(MGB)/dt is H) and (BSOC is M) and (CL(e) is I) then (HR is E)(SR is B) (1)
53. If (P(MGB) is MP) and (P(MGB)/dt is H) and (BSOC is M) and (CL(e) is I) then (HR is E)(SR is B) (1)
54. If (P(MGB) is HP) and (P(MGB)/dt is H) and (BSOC is M) and (CL(e) is I) then (HR is E)(SR is B) (1)

Figure-1. Fuzzy logic PMC surface maps and set of rules.

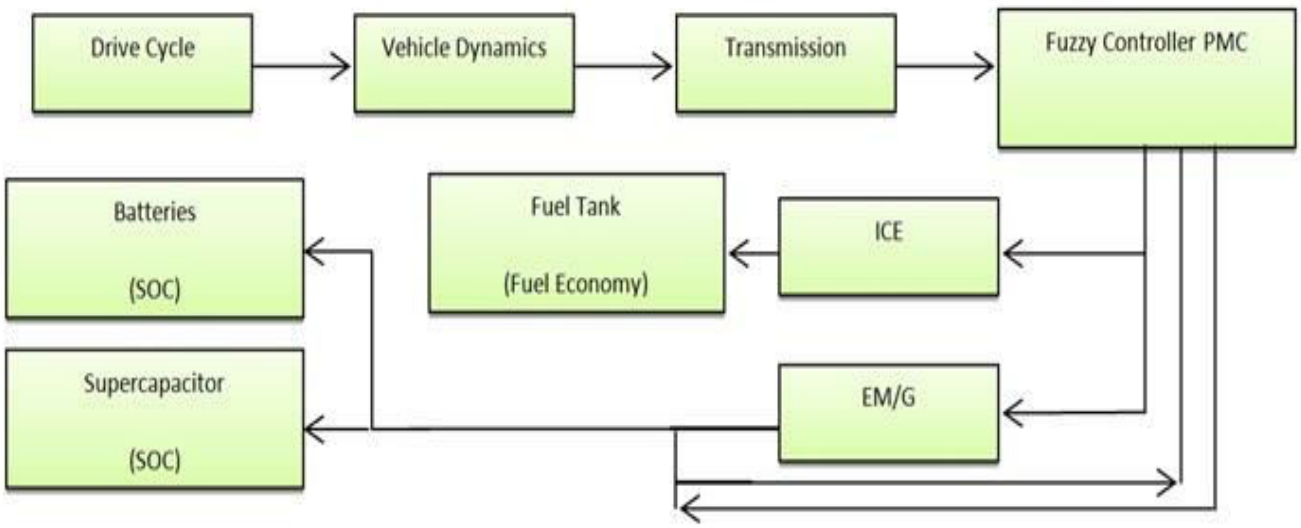

Figure-2. A diagram representing a complete HEV model using QSS approach.

And electrical energy consumed (or captured) known by integrating power consumed (or captured) by battery or supercapacitors, estimated using equation:

$$Electrical\ energy, EE\ (J) = \int P\ dt = \int VI\ dt \quad (4)$$

The total energy consumed by HEV is:

$$EC = E_f + EE_p + (-EE_n) \quad (5)$$

Where; EC is total energy consumed, E_f is fuel energy consumed, EE_p is electrical energy consumed, EE_n is electrical energy captured.

Electrical energy captured may either from ICE during on-board battery charging period and/or from electric motor during regenerative braking period.

RESULTS AND DISCUSSION

This controller was compared on NEDC (New European Driving Cycle) as shown in Figure-3, against an established work presented in [1]. Based on Figure-5, this HEV fuzzy logic PMC cumulative fuel consumption shows an increment of about 0.2 kg to 0.53 kg for NEDC compared to HEV dynamic programming (DP) controller which is at 0.33kg for the same drive cycle (Figure-4). This is an acceptable value range, although fuzzy logic PMC not close to optimal as expected, this controller will be improved.

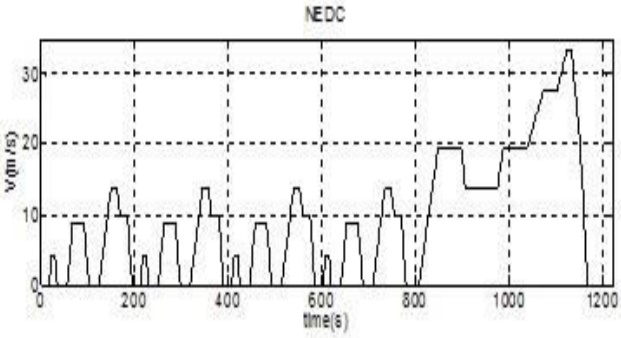

Figure-3. New european driving cycle (NEDC).

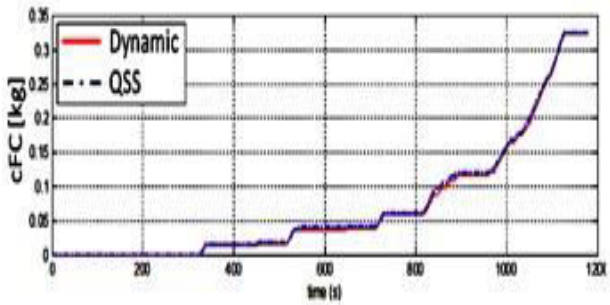

Figure-4. Cumulative fuel consumption based on NEDC drive cycle. [1].

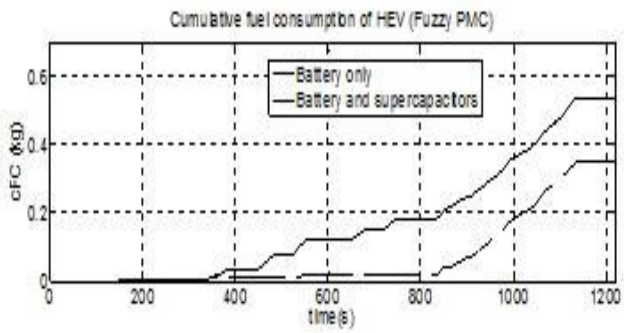

Figure-5. Cumulative fuel consumption based on NEDC drive cycle for combined power supply and battery only supply.

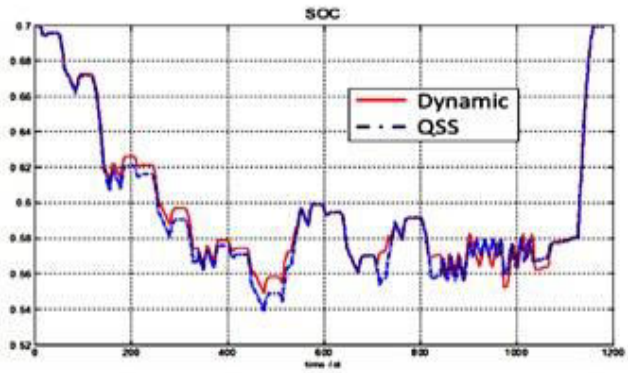

Figure-6. Battery SOC based on NEDC drive cycle [1].

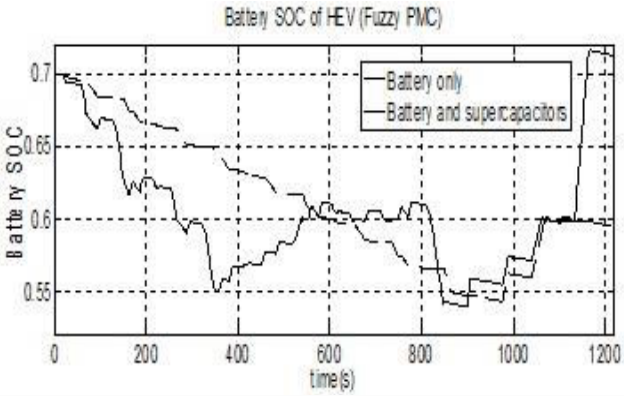

Figure-7. Battery SOC based on NEDC drive cycle for combined power supply and battery only supply.

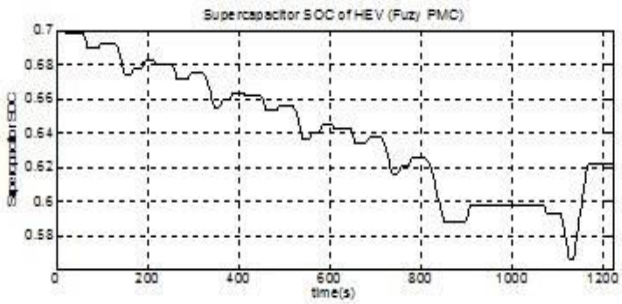

Figure-8. Supercapacitor SOC based on NEDC drive cycle.

After addition of supercapacitors, simulations were carried out to investigate its impact to HEV fuel economy. In Figure-6, Figure-7 and Figure-8, a comparison of cumulative fuel consumption, battery SOC and supercapacitors SOC; between combined power supply (CPS) and battery only supply (BS) is presented respectively. The results on fuel consumption and total energy consumption which calculated based on method explained earlier are summarized in Table-4. It shows that combined power supply (CPS) has lower fuel consumption at 88.9 mpg compared to battery only supply (BS) at 57.6 mpg. Also, lower total energy consumption at 19.21 MJ compared to BS at 24.42 MJ; energy consumption reduction of about 27%.

Table-4. HEV total energy consumption by BS and CPS.

Setup	m_f (mpg)	(%)	EC (MJ)	(%)
BS	57.6 mpg	-	26.4225 MJ	-
CPS	88.9 mpg	54.34	19.2172 MJ	27.27

This HEV model built using QSS shows excellent accuracy against dynamic modelling, this proved by battery SOC results comparison shown earlier, it lies within 2.8% margin against established result from Alberto's work. This battery SOC result also shows that fuzzy logic PMC works well and close to optimal ideal;

PMC optimized by DP. Although cumulative fuel consumption results shows significant increment (0.2 kg) by using fuzzy logic PMC, however such amount of error is within acceptable range due to the fact that fuzzy logic PMC is significantly much lower computational burden and low cost; reasons which makes it implementable as real time controller. Then, supercapacitor added to this HEV model and fuzzy logic PMC was modified. This results in lower fuel consumption and total energy consumption; as evidently proved by graph presented earlier, improvement of 54.45% and 27.27% respectively. This fuel or energy savings resulted mainly from significant reduction in cumulative fuel consumption when combined power supply is used, compared to battery only supply which consumed more fuel as higher period of on-board charging by ICE is required. This is probably due to lower energy conversion efficiency from chemical to mechanical in ICE (~25%-30%) compared to electrical to mechanical in EM (~70%-90%). Moreover, fuzzy logic PMC allows high power demand to be supplied from supercapacitors instead of battery or internal combustion engine; this surely improves fuel economy (because this reduce moment of engine operating at high rpm) and battery life. Also, total energy significantly reduced because supercapacitors addition allows higher regenerative braking efficiency; means more energy recaptured during braking. Results presented here shows supercapacitor addition to EV/HEV system and controlled by fuzzy logic probably had significant impact, but proper cost analysis of this addition was not carried out as this is not within scope of work.

CONCLUSIONS

In conclusion, the use of fuzzy logic PMC to manage power flow from internal combustion engine and electric motor shows good and practical performance against optimal ideal controller, it also shows good performance to manage power flow from battery and supercapacitors. Altogether, fuzzy logic PMC had resulted in better fuel economy and total energy consumption reduction.

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