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Comparison of Well-to-Wheel Efficiencies for Different Drivetrain Configurations of Transit Buses

Michael Schwertner and Ulrich Weidmann

The transportation sector, especially road transport, must reduce its energy consumption and emissions significantly. This requirement also applies to road-bound public transport, which uses mainly diesel buses. A reasonable measure for reaching this goal is to electrify the vehicle's drivetrain. During the past decade, several alternative technologies have evolved, namely, hybrid electric buses, fuel cell electric buses, and battery electric buses (BEBs). For a comparison of their energy efficiency, both the drivetrain's efficiency and the efficiency of the energy supply must be examined to determine well-to-wheel efficiency. This paper attempted to compare seven drivetrains for urban transit buses: diesel, natural gas, diesel–electric, hybrid electric (series and parallel), fuel cell electric, battery electric, and trolley bus. This comparison will become the main part of a more extensive model that supports decision making in bus procurement processes. The model will be as simple as possible. This factor makes it suitable also for the practitioner's use. Therefore, an analytic approach instead of a simulation tool was used. The model's outcomes were both total and specific energy consumption of four generic bus types operating on a dedicated bus line. The result of the study found that the trolley bus, closely followed by the BEB, was the most efficient, even when the share of renewable energy in electricity generation was low. The possibility to reduce specific energy consumption by increasing the occupation rate is outlined as well.

The transportation sector is energy-intensive and depends heavily on fossil energy. For example, according to Davis et al., the U.S. transportation sector uses 67% of U.S. total petroleum used. (*1*). Because of the growing uncertainty in petroleum supply, energy sources must be diversified. A possible way to achieve this diversification is to electrify the drivetrain of vehicles. Electricity can be generated from nearly any primary energy source, and the power network makes electric energy available nearly everywhere. An additional effect—and one of equal importance—is the reduction of pollutants, both air and noise. Although public transport already contributes to a more environmentally friendly transport sector, it can achieve further improvements. Possible measures in this context are either substituting alternative fuels for diesel fuel or replacing diesel buses by buses with alternative drivetrains, partly or fully electric.

In the public transport sector, the use of electric energy is not a new phenomenon: since the final decade of the 19th century, the growth of tram, subway, and suburban railway networks was possible only because of their electrification. The decline of these systems in many countries during the middle of the 20th century led to the situation in which public transport in a large number of cities relies mostly or exclusively on diesel buses. But even in cities with tram systems, trolley bus systems, or both, diesel buses operate on feeder lines. A significant potential for further electrification obviously still exists.

Within the past decade, several new propulsion systems have been under investigation. Today, predicting which of these systems will be introduced is difficult. While some systems are close to implementation, others are still in their test phase. In the near future, more and more public transport operators will be faced with the decision on which type of electric bus will replace the diesel bus. Until now, no methodology has been available to provide practitioners with assistance in those decision processes. An ongoing research project at the Institute of Transportation Planning and Systems, ETH Zurich, is seeking to develop an extensive model for supporting decisions on the choice of drivetrain systems. The main part of the model is formed by the comparison of energy efficiencies and is described here.

In this paper, a generic energy flow model is introduced. On the basis of the generic model, detailed models of seven drivetrain configurations are derived. These are a core part of the model used to estimate energy consumption, which is also described. As this model aims to be used by public transport operators and authorities, some efforts were made to keep it as simple as possible. Several outcomes of the model are presented and discussed.

PREVIOUS RESEARCH AND CURRENT SITUATION

During the past decade, a growing number of tests of different drivetrain systems for urban buses have been conducted. A first step toward electrification is the diesel hybrid electric bus (HEB). (The abbreviations and acronyms used in this paper are summarized in Table 1.) In the United States, such vehicles were evaluated at the National Renewable Energy Laboratory by Chandler et al. as early as 2002 (*2*) and by Chandler and Walkowicz in 2006 (*3*). On the basis of the outcomes of these (and other) tests, a life cycle cost model was developed by Golub et al. that helped operators in planning their bus procurement (*4*). In Europe, evaluations of HEBs began around 2010, but unfortunately, no results have been published. At least on hybrid electric vehicles, some theoretical contributions on energy consumption are available, and these findings could be transferred to

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TABLE 1 Abbreviations and Acronyms Used in This Study

Abbreviation or Acronym	Definition	Abbreviation or Acronym	Definition	Abbreviation or Acronym	Definition
Primary Energy Pathways		Energy Supply		Drive Train Configurations	
O	Crude oil	FS	Fuel station	DB	Diesel bus
NG	Natural gas	CS	Charging station	GB	Gas bus
C	Coal	CL	Contact lines	DEB	Diesel–electric bus
UO	Uranium ore	Energy Storage		HEBs	Series hybrid electric bus
RE	Renewable energy	FT	Fuel tank	HEBp	Parallel hybrid electric bus
Ex	Extraction	ES	Electricity storage	FCEB	Fuel cell electric bus
Pr	Production	Energy Conversion		BEB	Battery electric bus
Tr	Transport	ICE	Internal combustion engine	ETB	Electric trolley bus
Rf	Refining	FC	Fuel cell system	Other	
Di	Distribution	G	Electric generator	3~/=	Rectifier
En	Enrichment	EM	Electric motor	=/3~	Inverter
Co	Compression	Energy Transmission		=/=	Battery power converter
Lq	Liquefaction	RG	Reduction gear	BR	Braking resistor
PP	Power plant	AG	Automatic gearbox	S	Street
HV	High-voltage network	DA	Drive axle		
MV	Medium-voltage network				
PT	Power transformer				
EL	Electrolyser				

HEBs. For example, Katrasnik et al. compared the energy conversion efficiency of series and parallel hybrid electric vehicles by using an analytic simulation tool (*5*). Their main findings were that the parallel drivetrain was more efficient than the series drivetrain and that the fuel economy strongly depended on the type of driving cycle.

In the United States, the focus seems to be on fuel cell electric buses (FCEBs) today. According to Eudy and Gikakis, seven demonstration projects were ongoing, with 38 active FCEBs in 2013 (*6*). During the tests, tank-to-wheel efficiency was measured and showed that FCEBs roughly doubled the traveled distance per diesel gallon equivalent of diesel buses. Some European cities have had tests with FCEBs, too. As with European HEBs, no results from these actual demonstration projects have been published. An overview of the worldwide status of FCEBs was assembled by Hua et al., who showed an interesting figure for the efficiency improvement by hybridization: 9 kg/100 km hydrogen consumption for a hybrid FCEB compared with 22 kg/100 km for a nonhybridized FCEB in London (*7*).

Battery electric buses (BEBs) are being evaluated as a third alternative system. According to Lajunen, BEBs (and plug-in HEBs) have the best potential for reducing energy consumption. BEB tests are ongoing in several European cities, for example, in Milton Keynes in the United Kingdom (*8*). Miles and Potter reported on first experiences there (*9*). In all the test systems, the approach of opportunity charging is used (i.e., charging with high power at dedicated stops along the line during the time needed for embarking and disembarking of passengers). This technology allows reducing both the battery size and especially its weight significantly, as storage of the energy for the whole day is not necessary. Only lithium ion batteries provide the power density required for opportunity charging. Some experiences with these batteries used in BEBs and FCEBs were summarized by Brecher (*10*).

The electric trolley bus is a proven full-electric bus technology, and it is even slightly more energy-efficient than BEBs. In several countries, such as Switzerland, it is a means of transport comparable to trams in relation to operating performance. Thus, one may also reasonably include the electric trolley bus in transport system comparisons.

The literature examples cited here consider only one, and sometimes two, drivetrain systems. In contrast, research on the comparison of a larger number of drivetrain configurations for urban buses is scarce. Furthermore, the simulation tools used for determining energy consumption are often not suitable for practitioners because of their complexity. These situations led to a research project at the Institute for Transport Planning and Systems, ETH Zurich, to develop a model that makes system comparisons as simple as possible. It does not need specialized software tools because it is implemented in Microsoft Excel and uses the analytic attempt, a tool presented in the following section.

COMPARISON OF DIFFERENT DRIVETRAINS

Energy Flow Model

Efficiency must be evaluated on the basis of primary energy (well-to-wheel efficiency). To achieve this evaluation, a two-step approach was chosen. First, the tank-to-wheel efficiency of different drivetrain configurations was evaluated. Second, an attempt was made to estimate the amounts of primary energy needed (well-to-tank efficiency). Then, both parts of the energy flow were combined to give the well-to-wheel efficiency.

The energy flow from the primary source to the wheels can be summarized by the simple generic model of energy flow shown in Figure 1*a*. Each block in the model usually contains more than one

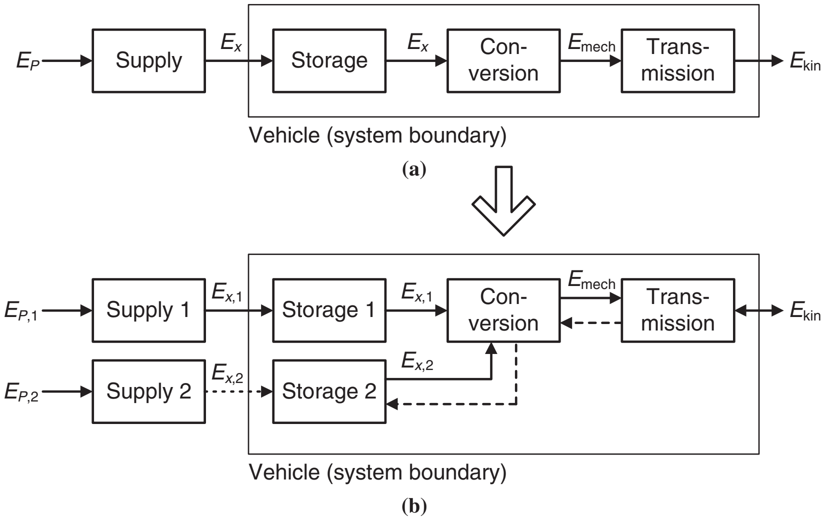


FIGURE 1 **Generic models of energy flow: (*a*) basic and (*b*) extended model.**

subprocess. The symbols used in the figure represent the following energy forms:

- E_P = primary energy,
- E_x = energy type suitable for storage on a vehicle,
- E_{mech} = (unspecified) mechanical energy, and
- E_{kin} = kinetic energy (i.e., translational motion).

New technologies have evolved in the past decade to make this simple model insufficient to describe all energy flows. Hybrid drivetrains, in particular, as their name indicates, convert kinetic energy from more than one energy source. Therefore, the model must be adapted. Figure 1*b* shows the extended model. The main reason for this adaption is the use of a second energy type within the drivetrain, usually electric energy, to allow the recovery of energy during braking (dashed arrows in Figure 1*b*). Furthermore, the dotted arrows in Figure 1*b* indicate the possibility of an additional energy supply (e.g., loading the battery), as with plug-in hybrid electric vehicles. This adapted model is suitable for derivation of specific schemes of energy flow for the different drivetrain configurations. The schemes showing electric drivetrains use only three-phase asynchronous traction motors, the standard configuration today. Obsolete technologies still in operation [e.g., direct-current (DC) chopper control] are omitted here.

Drivetrain Configurations

Seven drivetrain configurations were analyzed; their schemes can be found in Figure 2. All of them are, though to very different extents, in use today. The dominant type is, of course, the diesel bus (Figure 2*a*). Diesel fuel has a high energy density, which makes it easy to store, even when space is limited, as it is on road vehicles. Usually, the vehicle carries the necessary amount for a whole day to provide maximum operational flexibility. The internal combustion engine converts the chemical energy via thermal energy to mechanical energy. Energy recovery during braking is not possible, but the engine's waste heat is used for heating the passenger compartment.

For the gas bus, usually driven by natural gas, the same scheme of energy flow applies as for the diesel bus (Figure 2*a*). Thus, the conditions mentioned for the diesel bus are also valid here.

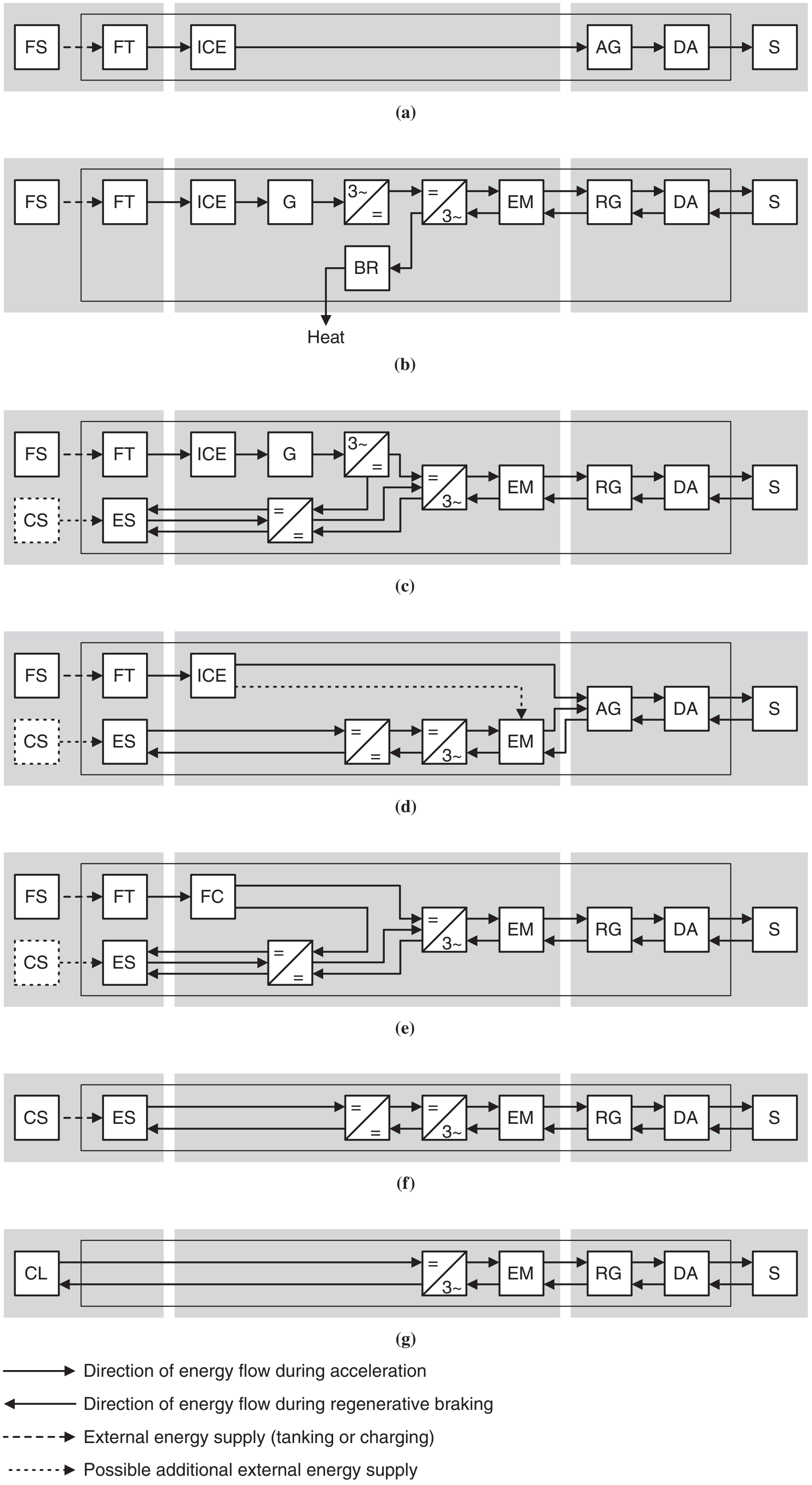
In diesel–electric buses (Figure 2*b*), an electric transmission replaces the mechanical gearbox. Thus, the engine does not have to be near the drive axle, so configuring the passenger compartment is easier, and construction of a 100% low-floor bus is possible. In addition, the vehicles accelerate more smoothly, and electric braking reduces the wear of the mechanical brakes. Today, only duo buses use this configuration, when operating in diesel mode.

An electric drivetrain works much more efficiently when it is equipped with an electricity storage system, usually a battery. This converts a diesel–electric bus to a (series) diesel HEB. Its main principle is the simultaneous use of two energy sources: diesel fuel and electricity. The two basic types are series hybrid (Figure 2*c*) and parallel hybrid (Figure 2*d*). Series hybrid buses have no mechanical connection between the diesel engine and the wheels. Propulsion is therefore always electric, with electricity provided from the battery, the generator, or both. Parallel hybrids differ significantly, because the diesel engine in a diesel bus is connected to a mechanical gearbox. The electric motor is mounted on the same drive shaft, providing additional torque when needed. Uncoupling the diesel engine also allows pure electric running. Energy savings are, in both cases, achieved by three means:

- Recuperation of energy during braking,
- Switching off the diesel engine when not needed, and
- Downsizing the diesel engine.

The last measure means that the engine is less powerful and thus unable to provide the needed maximum power; engines in hybrid buses usually have just about half the power as those in diesel buses. If the power need is higher, the battery provides the difference. This alternative allows the diesel engine to operate much more often near its point of maximum efficiency, which is near the point of maximum power.

FCEBs are another possibility for the application of electric drivetrains (Figure 2*e*). They are propelled by pure hydrogen, usually



(a)

(b)

(c)

(d)

(e)

(f)

(g)

FIGURE 2 Specific schemes of energy flow by drivetrain configuration: (*a*) DB and GB, (*b*) DEB, (*c*) HEBs, (*d*) HEBp, (*e*) FCEB, (*f*) BEB, and (*g*) ETB.

TABLE 2 Energy Efficiency Factors of Drivetrain Subsystems in Driving Mode

Subsystem	DB	GB	DEB	HEBs	HEBp	FCEB	BEB	ETB
FT	1.00	1.00	1.00	1.00	1.00	0.98	—	—
ES	—	—	—	—	—	—	0.92	—
ICE	0.38	0.34	0.40	0.42	0.38	—	—	—
FC	—	—	—	—	—	0.55	—	—
G	—	—	0.93	0.93	—	—	—	—
=/=	—	—	—	—	—	—	0.98	—
3~/=	—	—	0.98	0.98	—	—	—	—
=/3~	—	—	0.98	0.98	—	0.98	0.98	0.98
EM	—	—	0.93	0.93	—	0.93	0.93	0.93
AG/RG	0.93	0.93	0.95	0.95	0.93	0.95	0.95	0.95
DA	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Total (η_d)	0.33	0.30	0.30	0.31	0.33	0.44	0.73	0.81

NOTE: — = not applicable.
SOURCE: Authors' estimations, partly based on examples given by Hondius (*11, 12*).

stored in high-pressure tanks. The main advantage of FCEBs is that the fuel cell system efficiently converts hydrogen directly to electricity. Some other fuel cell systems use methanol, which can be stored as diesel fuel is. However, their efficiency is lower, and the vehicle would not be emissions free, as carbon dioxide (CO_2) is emitted. Today's FCEBs are always hybrid buses because they are equipped with a battery, which allows recovery of braking energy and reduces the fuel cell's peak load.

The highest degree of electrification in the drivetrain is represented by battery buses (Figure 2*f*) and trolley buses (Figure 2*g*). Electric energy is provided either intermittently (BEBs) or continuously (electric trolley bus). In the latter case, a vehicle-bound energy storage system is not required, but for more flexibility, trolley buses are mostly equipped with an auxiliary power unit. If this auxiliary unit has a normal bus diesel engine, the vehicle is called a duo bus, because it is also fully capable of running when the bus has no contact line.

Energy Efficiency

Tank-to-Wheel Efficiency

The energy flow schemes allow comparison of energy consumptions, provided that an efficiency factor is assigned to each subsystem within the drivetrain. To estimate energy efficiency on the system-level vehicle (i.e., tank-to-wheel efficiency), the values for both driving (Table 2) and recuperation modes (Table 3) must be derived. Several values shown in these tables are quite rough estimations and should therefore be treated with some care. Their order of the subsystems is widely independent of vehicle size. Thus, the values in Tables 2 and 3 are used for all vehicle types equally.

In recuperation mode, not only is drivetrain efficiency relevant, but also—independent of the drivetrain configuration—not all kinetic energy can be recovered. The forces resulting from rolling and drag resistance have a braking effect that is not part of the braking force

TABLE 3 Energy Efficiency Factors of Drivetrain Subsystems in Recuperation Mode

Subsystem	DB	GB	DEB	HEBs	HEBp	FCEB	BEB	ETB
DA	—	—	—	0.94	0.94	0.94	0.94	0.94
AG/RG	—	—	—	0.95	0.93	0.95	0.95	0.95
EM	—	—	—	0.93	0.93	0.93	0.93	0.93
3~/=	—	—	—	0.98	0.98	0.98	0.98	0.98
=/=	—	—	—	0.98	0.98	0.98	0.98	—
ES[a]/CL[a]	—	—	—	0.85	0.85	0.85	0.85	0.85
=/=	—	—	—	0.98	0.98	0.98	0.98	—
=/3~	—	—	—	0.98	0.98	0.98	0.98	0.98
EM	—	—	—	0.93	0.93	0.93	0.93	0.93
AG/RG	—	—	—	0.95	0.93	0.95	0.95	0.95
DA	—	—	—	0.94	0.94	0.94	0.94	0.94
Total (η_d)	—	—	—	0.54	0.52	0.54	0.54	0.56

NOTE: The order of subsystems from top to bottom represents the complete flow for the recuperated energy (from wheels to battery and back to wheels).
[a] Combined efficiency for charging and discharging (0.92 ∗ 0.92 = 0.85).
SOURCE: Authors' estimations, partly based on examples given by Hondius (*11, 12*).

generated by the drivetrain and therefore cannot be recovered. For buses, around 12% to 15% of the kinetic energy is lost, a figure that depends on vehicle size and driving cycle, while for trams the corresponding values are between 6% and 7% because of lower rolling resistance. If the storage system has restrictions related to maximum power or capacity, an additional amount of energy is lost. In this case, the recovery factor must be reduced.

The calculated tank-to-wheel energy consumptions were found to be good matches for the fleet averages of Zurich's tram and bus operator VBZ.

Well-to-Tank Efficiency

Finally, the efficiency of the energy supply chain from raw material to storage on the vehicle (well-to-tank efficiency) is needed. The energy flow can be described by using an approach similar to that used for modeling the drivetrains. The supply chain of fossil fuels (diesel and natural gas) is summarized in Figure 3*a.* For electricity supply, the widespread system of centralized generation and distribution is assumed. Four main primary sources are included: coal, natural gas, nuclear, and renewable energy (Figure 3*b*). For hydrogen, electrolytic generation is assumed (Figure 3*c*). In addition, the most challenging part is to get the efficiency values. Edwards et al. estimated the efficiency of several well-to-tank supply chains (*13*), and they gave a specific energy for each step, which needed to be converted to the efficiency factors shown in Figure 3. Those values were calculated on the basis of the European energy supply system. The aggregated values are summarized in Table 4.

Renewable energy's availability is practically unlimited, so the efficiency of generating electricity by using wind, water, or solar power can be neglected. Therefore, the generation efficiency factor was set

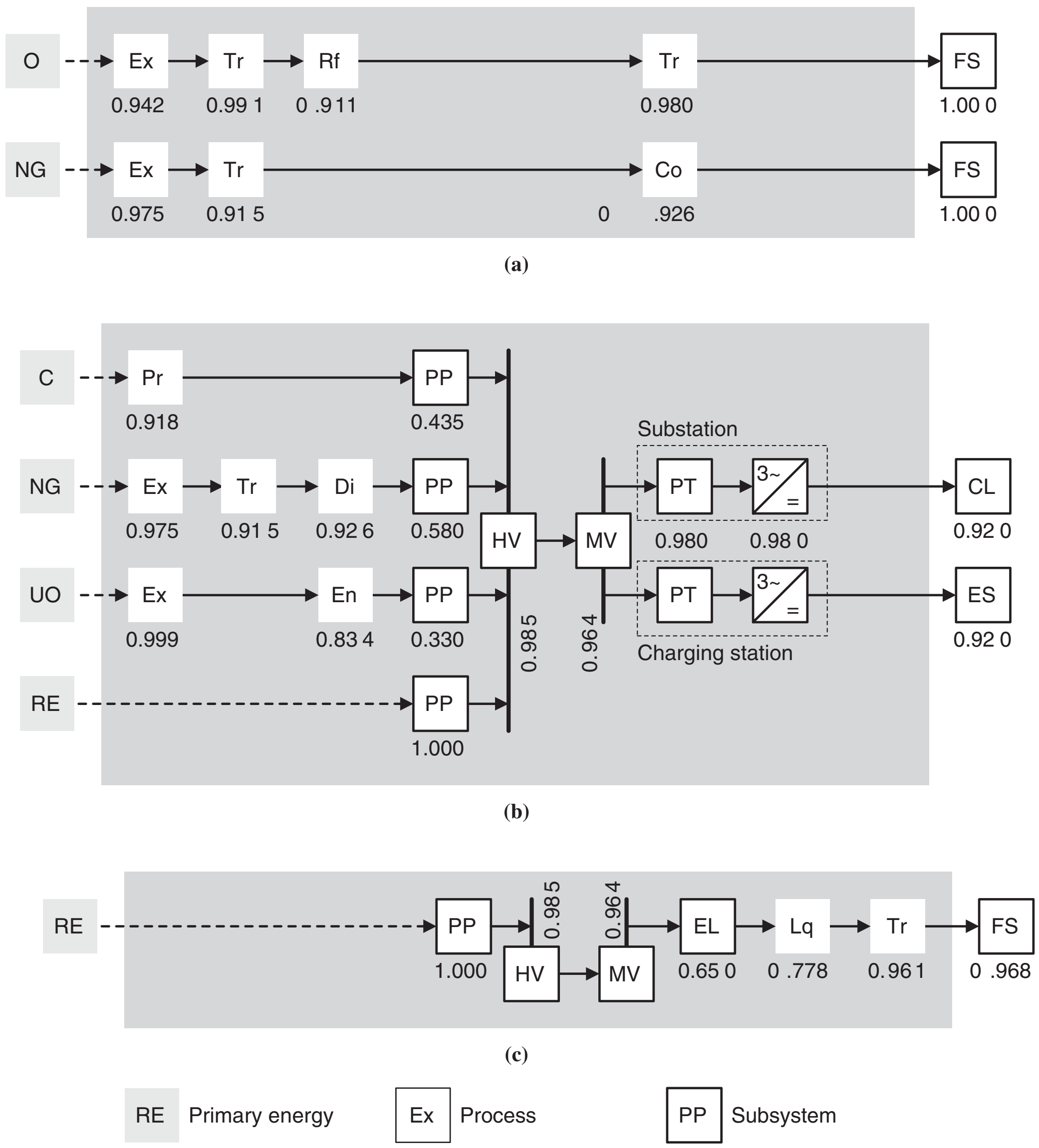


FIGURE 3 Energy flow schemes for energy supply, including process and subsystem efficiencies: (*a*) fossil fuels, (*b*) electricity generation, and (*c*) electrolytic generation of hydrogen.

TABLE 4 Well-to-Tank Efficiency of Energy Supply

Traction Energy	Share[a] (%)	Primary Energy	Supply Efficiency
Diesel oil	na	Crude oil	0.83
Natural gas	na	Natural gas	0.83
Electricity	3.4	Coal	0.38
	2.5	Natural gas	0.49
	37.6	Uranium ore	0.26
	56.5	Renewable energy	0.95
	na	Total (from MV network)	0.66
	na	Total (from contact line)	0.58
	na	Total (from battery)	0.58
Hydrogen	na	Renewable energy	0.45

NOTE: na = not applicable.

[a] Swiss electricity generation mix.

SOURCE: Values from Figure 3; shares of primary energy for electricity generation were derived from Swiss electricity statistics 2013 (*14*).

to one, while transmission efficiency was regarded as equal to the other sources (power stations feeding a central distribution network).

Calculation of Energy Consumption

The efficiency factors are important input parameters for the energy demand calculation model, which uses the SORT (standardized on-road test) driving cycles developed by UITP (International Association of Public Transport) (*15*). The model's calculation algorithm estimates the energy consumption in the five steps shown in Figure 4. The algorithm basically follows the approach used by Ott et al., although in a simplified manner (*16*). Besides the SORT cycles, some general vehicle data (e.g., vehicle weight, number of seats, specific rolling resistance) as well as several parameters describing the bus line (e.g., number of SORT cycles, interval, and turnaround times) are required as input values. The model compares four generic bus types defined by their length and includes a tram for comparison purposes: 9.5 m (30 ft) and 12 m (40 ft) buses, both two-axle nonarticulated; 18-m (60-ft), three-axle articulated and 24-m (80-ft) four-axle double-articulated buses; and a 36-m (118-ft) low-floor tram. An average occupation factor determines the number of passengers transported.

First, the total amount of energy W (W_{total}) needed at the wheelbase for overcoming rolling energy (W_{WR}) and drag resistance energy (W_{WD}) for acceleration (acc) and for steady speed running (ssr), as well as for acceleration itself (kinetic energy W_{kin}), is calculated:

$$W_{\text{total}} = W_{\text{kin}} + W_{\text{WR,acc}} + W_{\text{WR,ssr}} + W_{\text{WD,acc}} + W_{\text{WD,ssr}}$$

Then, the recovery factor n_{recup} is calculated by using the formula (with "dec" meaning deceleration):

$$n_{\text{recup}} = 1 - \frac{W_{\text{WR,dec}} - W_{\text{WD,dec}} - W_{\text{th}}}{W_{\text{kin}}}$$

where W_{th} represents the energy lost by mechanical braking (or dissipated by braking resistors) when the electricity storage system is fully loaded or unable to cope with the braking power. The maximum recuperable energy, W_{recup}, can now be computed by using n_{recup} and the efficiency factor η_{recup} shown in Table 3.

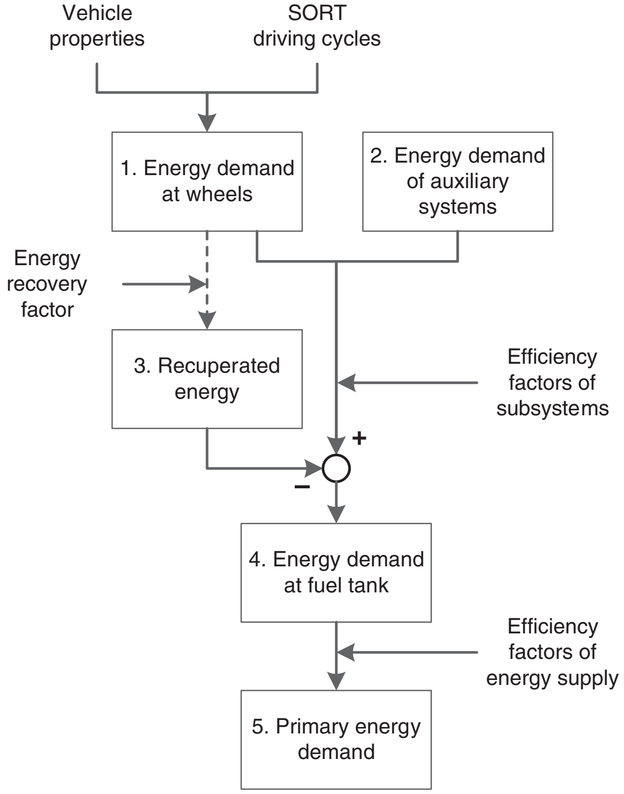


FIGURE 4 Basic structure of calculation model.

$$W_{\text{recup}} = n_{\text{recup}} \cdot \eta_{\text{recup}} \cdot W_{\text{kin}}$$

W_{recup} represents the amount of energy that can be reused after its having passed the whole pathway from wheels to storage and back to the wheels. Thus, the energy that has to be provided to the vehicle, W_s, can be derived simply by

$$W_s = \frac{W_{\text{total}} - W_{\text{recup}}}{\eta_d}$$

where η_d represents the drivetrain's efficiency, according to Table 2. The last step is dividing W_s by the appropriate efficiency factor from Table 4 to get the amount of primary energy needed. Only on this basis is a reasonable comparison possible.

Results

An example of the maximum recuperation potential is shown in Figure 5, in which the Index 1 at rolling and drag resistance indicates that the values include both acceleration and steady-speed running, while Index 2 marks deceleration. Compared with the total energy at the wheelbase, the theoretical recuperation potential is 35%. However, as the energy consumption of auxiliaries and heating and cooling is not included here, the recuperation potential is significantly lower in reality.

As main results, the model provides values for both total and specific energy consumption. Figure 6 shows specific energy consumption for different drivetrain configurations of a 12-m (40-ft)

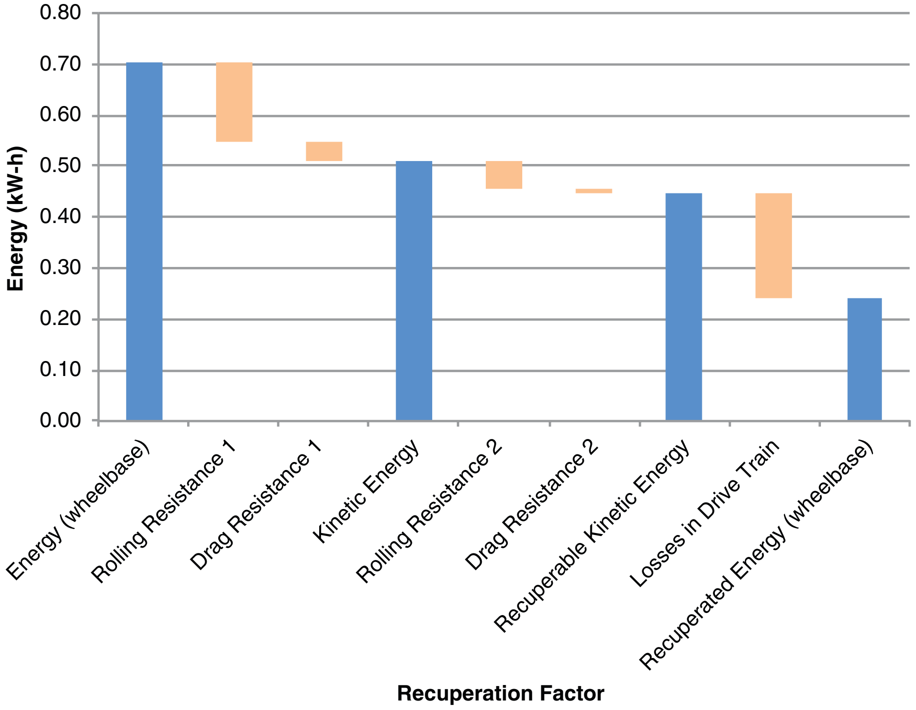
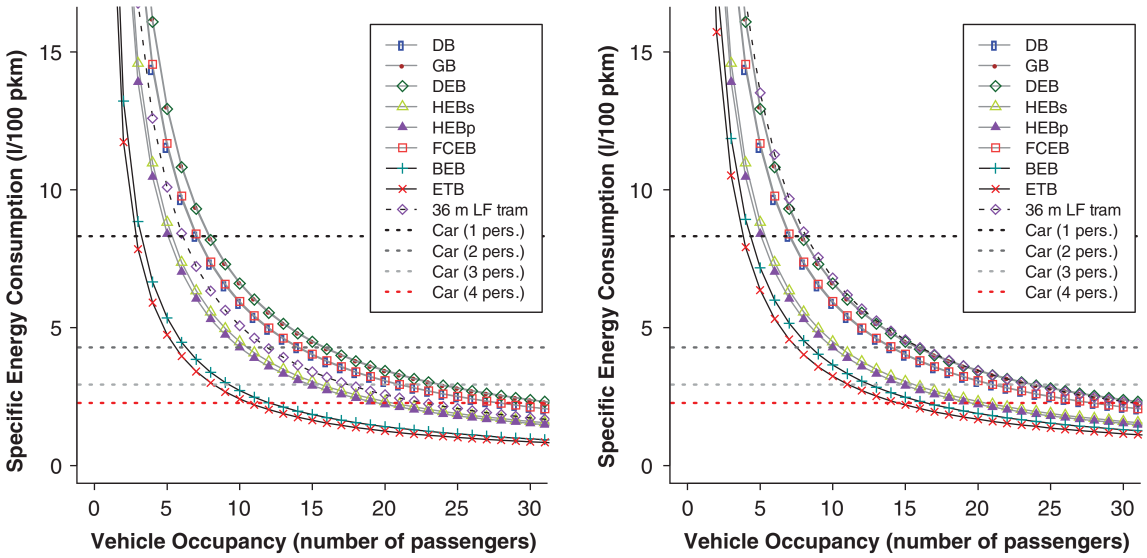


FIGURE 5 Theoretical recuperation potential of HEBs 12-m (40-ft) bus (SORT 1 driving cycle and occupancy factor 20%, with only traction energy considered).



(a) (b)

FIGURE 6 Specific energy consumption for 12-m (40-ft) bus, according to occupancy and drivetrain type, compared with tram and medium-sized car, for one SORT 1 driving cycle: (*a*) mix of electricity generation for Switzerland and (*b*) mix of electricity generation for Germany (L/100 pkm = liters of diesel equivalent per 100 passenger kilometers; LF = lower floor; pers. = persons).

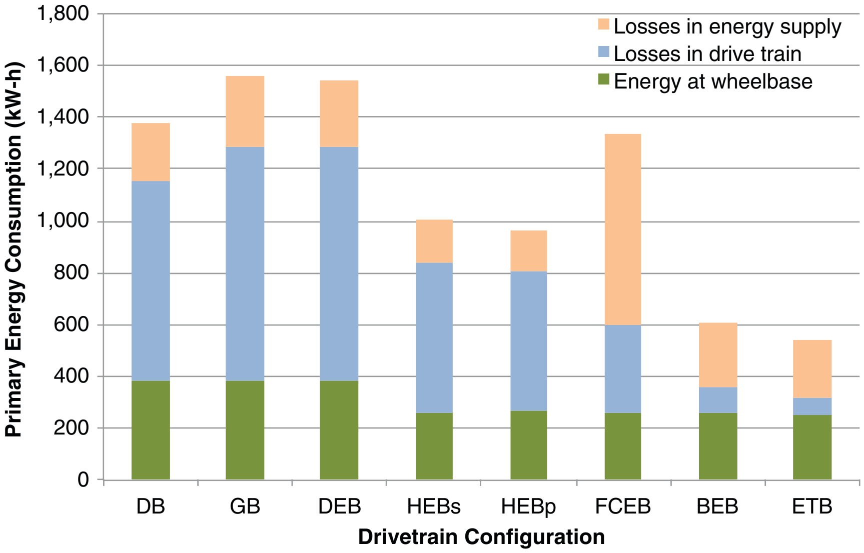


FIGURE 7 Energy consumption of 12-m (40-ft) bus during 19 h of operation for line length of 12.6 km (7.8 mi) and average speed of 16.5 km/h (10.3 mph).

bus. For comparison, the values for a tram and a car are included as well. Of course, specific energy consumption decreases when more passengers are on the bus. Here, the most interesting values are the points at which the bus becomes more efficient than a car. In both examples, the trolley bus, closely followed by the battery bus, has the best energy efficiency. For the Swiss example, this is not surprising, given Switzerland's high share of renewable energy (mostly from water power). However, even with nearly 40% of electricity produced from coal, as in Germany, the full-electric buses still perform significantly better than do hybrid buses.

Figure 7 shows an example of total energy consumption during a full 19-h operation period on an urban line 12.6-km (7.8-mi) long, at an average speed of 16.5 km/h (10.3 mph). The lower value for energy at the wheelbase indicates which drivetrain is capable of recuperation. For the diesel (electric) and gas buses, the losses within the drivetrain are more than twice as high as the amount of energy needed at the wheelbase.

The comparison of short buses with a much longer tram might seem arbitrary, but it illustrates quite well the energy efficiency of trams. Despite being much heavier, a tram with an occupation factor of just 10% is more energy-efficient than a diesel bus with a factor around 30%, at least in the Swiss example.

Carpooling is a strong measure for making the use of automobiles more energy-efficient. As Figure 6 shows, a car with four passengers (including the driver) is as efficient as a 12-m diesel bus with around 30 passengers (47% occupancy rate). Although the energy-equal occupancy of full-electric buses is just 23% (around 15 passengers in the German example), the authors strongly recommend that the public transport sector further improve its energy efficiency.

CONCLUSIONS

Both trolley and battery buses are the most energy-efficient systems, even when the share of renewable energy in electricity generation is relatively low. The well-to-tank efficiency of electricity supply must be lower than around 0.35 for hybrid buses to become more efficient than battery (and trolley) buses. Thus, in most cases, a shift to full-electric buses is more reasonable, at least from the energy perspective.

The energy efficiency of FCEBs does not depend only on how the hydrogen is produced; also important is the manner in which this process is considered in the efficiency calculation. One could say that, as renewable energy is virtually infinite, the efficiency of the entire hydrogen supply process could be neglected. Here, a more moderate position is proposed by neglecting only the efficiency of electricity generation. In the authors' point of view, using electricity directly is more reasonable than producing hydrogen, transporting it, and transforming it to electricity later. However, this opinion may need to change in the future. Given an electricity supply system based exclusively on renewable energy, the system has to balance the gap between power supply and demand by using storage systems. Here, producing hydrogen as a storage medium is possible. Increased hydrogen availability would make it more viable for use in transport systems.

Finally, besides the influence of drivetrain technology, the occupation rate is a factor of equal importance: The more passengers riding a bus, the less (specific) energy is consumed. Increasing patronage is a cheap, although not always easily achievable, measure for improving efficiency. Furthermore, it generates more income for the operating company. Or, in other words, from the environmental perspective, it is better to have well-frequented diesel buses than empty battery buses.

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