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A comparative analysis of well-to-wheel primary energy demand and greenhouse gas emissions for the operation of alternative and conventional vehicles in Switzerland, considering various energy carrier production pathways

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HIGHLIGHTS

- Operational GHG emissions and energy demand are found for alternative drivetrains.
- Well-to-wheel results are compared for several H_2/electricity production pathways.
- Pluggable electric cars (PECs) yield the lowest WTW GHG emissions and energy demand.
- Fuel cell car WTW results are on par with PECs for direct chemical H_2 production.
- ICE and hybrid cars using biogas and CNG also yield some of the lowest WTW results.

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ABSTRACT

This study provides a comprehensive analysis of well-to-wheel (WTW) primary energy demand and greenhouse gas (GHG) emissions for the operation of conventional and alternative passenger vehicle drivetrains. Results are determined based on a reference vehicle, drivetrain/production process efficiencies, and lifecycle inventory data specific to Switzerland. WTW performance is compared to a gasoline internal combustion engine vehicle (ICEV). Both industrialized and novel hydrogen and electricity production pathways are evaluated. A strong case is presented for pluggable electric vehicles (PEVs) due to their high drivetrain efficiency. However, WTW performance strongly depends on the electricity source. A critical electricity mix can be identified which divides optimal drivetrain performance between the EV, ICEV, and plug-in hybrid vehicle. Alternative drivetrain and energy carrier production pathways are also compared by natural resource. Fuel cell vehicle (FCV) performance proves to be on par with PEVs for energy carrier (EC) production via biomass and natural gas resources. However, PEVs outperform FCVs via solar energy EC production pathways. ICE drivetrains using alternative fuels, particularly biogas and CNG, yield remarkable WTW energy and emission reductions as well, indicating that alternative fuels, and not only alternative drivetrains, play an important role in the transition towards low-emission vehicles in Switzerland.

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1. Introduction

The transportation sector is the largest contributor to GHG emissions in Switzerland, accounting for over 30% of annual emissions (see Fig. 1a). Passenger cars alone account for nearly 70% of emissions within this sector (Fig. 1b). The Swiss passenger car fleet today is dominated by gasoline and diesel internal combustion engine (ICE) vehicles; however, several alternative drivetrain technologies and energy carriers exist with the potential to reduce transportation sector emissions. Alternative drivetrains include hydrogen fuel cell, battery-electric, and hybrid-electric drivetrains; and alternative energy carriers include hydrogen, electricity, biogas, and CNG.

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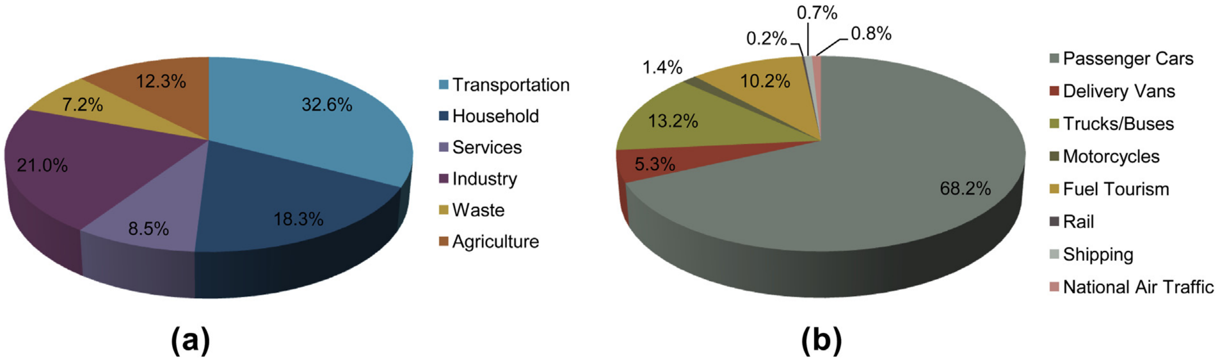


Fig. 1. Annual GHG emissions in Switzerland by sector (a) [1] and within the transportation sector (b) [2].

Given the range of drivetrain, energy carrier, and energy carrier production processes available, it is imperative to understand the well-to-wheel (WTW) primary energy demand and cumulative greenhouse gas (GHG) emissions associated with each option. This information enables a comparative analysis of drivetrain options and is essential in the domain of public policy decision-making in order to develop a roadmap for electric mobility in Switzerland, reduce road transport emissions, and plan infrastructure.

Primary energy (PE) refers to the energy contained in raw fuels, such as oil, natural gas, or biomass, for example. When primary energy undergoes a conversion process, it can be transformed into secondary or useful energy, such as electricity or hydrogen fuel. The primary energy demand for electricity production using a natural gas power plant, for example, encompasses all upstream energy inputs from resource extraction to plant construction and disposal (also known as gray energy). Cumulative greenhouse gas emissions refer to the equivalent carbon dioxide emissions associated with the processing and combustion of primary energy. A well-to-wheel analysis considers PE demand and GHG emissions from resource extraction to vehicle propulsion. Together, WTW energy demand and GHG emissions can serve as performance indicators for alternative drivetrains compared to conventional gasoline internal combustion engines.

This study aims to determine the WTW primary energy demand and GHG emissions associated with the operation (i.e., energy carrier demand) of alternative drivetrains while considering a broad range of hydrogen production and electricity generation pathways in the Swiss context. All energy carrier lifecycle inventory data applies to end-use in Switzerland. The hydrogen production processes investigated include mature technologies, such as steam methane reforming (SMR), gasification, and partial oxidation, as well as relatively novel processes, such as solar thermochemical decomposition and photobiological splitting. A number of drivetrains and energy carriers are examined. Vehicles include fuel cell, electric, hybrid-electric, and conventional ICE drivetrains, while energy carriers include gasoline, diesel, compressed natural gas, biogas, hydrogen, and electricity.

A WTW analysis is also presented according to natural resource categories. This approach provides a unique perspective, pertinent to questions regarding optimal resource allocation in the context of primary energy demand and GHG emissions.

Several studies have presented lifecycle or well-to-wheel energy and greenhouse gas emissions analyses for alternative vehicles and hydrogen production processes; however, studies in the Swiss context, an evaluation according to natural resource categories, and a comprehensive comparison including both mature and novel hydrogen production processes are not available. The scope of current studies is limited to conventional means of hydrogen production, including electrolysis, steam methane reforming, and coal gasification. For instance, Huang and Zhang examine the well-to-wheel energy demand and GHG emissions for hydrogen production via steam methane reforming, coal gasification, and electrolysis for fuel cell vehicles in Ref. [3]. Campanari et al. also perform a WTW analysis for the same hydrogen production pathways in Ref. [4], but they consider ICE, electric, and hybrid fuel cell vehicles, in addition to fuel cell vehicles. Comparative assessments for a similar range of drivetrains are presented in Refs. [5,6,7,8,9,10], but again, the range of hydrogen and electricity generation pathways is limited to conventional means. An exergetic lifecycle assessment (LCA) focused on hydrogen production via electrolysis and SMR for automotive applications is also presented in Refs. [11,12].

This study is novel in three respects. First, it provides a comprehensive, comparative analysis which considers the performance of both commercially-mature and novel hydrogen production processes, multiple electricity generation pathways, and several alternative drivetrains. Second, it applies directly to the Swiss situation; and third, the analysis offers a unique comparison of drivetrain and energy carrier production pathways based on natural resource categorizations.

2. Objective

The objective of this investigation is to determine the well-to-wheel primary energy demand and greenhouse gas emissions associated with the operation of a number of drivetrains, while considering an array of possible hydrogen and electricity production pathways.

The aim is to identify the drivetrain and production pathways which demonstrate the greatest potential to reduce operational WTW energy demand and GHG emissions compared to a conventional gasoline ICE vehicle (ICEV) in the Swiss context. Several possible natural resource pathways are considered. A reference passenger vehicle is defined and serves as the basis for this comparison. Vehicle configurations improving upon the WTW energy demand and GHG emissions of the gasoline ICEV are denoted as competitive options for the purposes of this study.

3. Background information

The following sections provide information on the hydrogen production processes and electricity mixes evaluated in this investigation.

3.1. Hydrogen production processes

3.1.1. Electrolysis

3.1.1.1. Low temperature electrolysis. Electrolysis is a process in which a direct electric current is applied to water via electrodes in an electrolyser, causing H_2O to dissociate into its constituent parts: hydrogen (H_2) and oxygen (O_2). It is a commercially viable approach for hydrogen production and can be applied on a small or large scale [13].

The low temperature electrolysis model described by the US National Renewable Energy Lab (NREL) in Ref. [14] is applied in this study. This model uses a standalone, alkaline electrolyser system, powered by an electric grid. The total hydrogen production capacity of the system is 52 300 kg H_2/day [14].

The main energy input to this process is electricity. It is assumed that water is readily available and requires negligible processing energy.

3.1.1.2. High temperature electrolysis. Electrolysis is most efficient at high temperatures. During high temperature electrolysis, heat is applied to the reaction in order to improve efficiency. Due to improved process efficiency, less input electricity is required compared to low temperature electrolysis.

The model developed by Technology Insights in Ref. [15] is applied in this study. Electricity is supplied from the electric grid and heat is supplied by a nuclear power plant. The electrolyser system delivers 815 616 kg H_2/day.

The main energy inputs to this process are electricity and heat. It is assumed that water requires negligible input energy and heat is delivered by a nuclear power station.

3.1.2. Solar thermochemical dissociation

A thermochemical cycle refers to a loop in which chemical reactions and heat are used to split water into hydrogen and oxygen. Solar thermochemical cycles demonstrate the potential for high conversion efficiencies [16]. The solar thermal dissociation of zinc oxide (ZnO) is examined in this study. The cycle is illustrated in Fig. 2.

Zinc (Zn) reacts with H_2O in the hydrolysis reactor to produce ZnO and H_2. The ZnO is then cycled back to the solar reactor where it is broken down into O_2 and Zn again. Zn is then recycled back to the hydrolysis reactor.

The main energy inputs to this process are electricity and solar energy. Electricity is required for processing and compressing hydrogen gas. It is assumed that water is readily available and requires negligible processing energy.

3.1.3. Photobiological splitting

Photobiological splitting uses solar energy to harness photosynthesis in organisms, such as plants, algae, and cynobacteria, in order to split water molecules and produce hydrogen. Photobiological splitting presents the advantage of using solar energy directly, which has to potential to be more efficient than using solar energy in a double conversion process to first grow biomass and then use biomass to produce hydrogen [18].

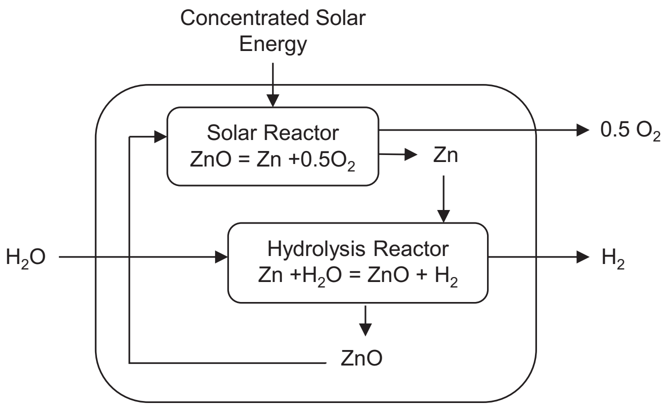


Fig. 2. Solar thermal dissociation of ZnO [17].

The theoretical study by Prince and Kheshgi in Ref. [19] is referenced in this investigation. One of two enzymes is used for hydrogen production: hydrogenase or nitrogenase. Additionally, two main pathways for biophotolysis are possible: direct or indirect biophotolysis.

Direct biophotolysis refers to the simultaneous evolution of hydrogen and oxygen during biophotolysis. During indirect biophotolysis, the evolution of oxygen and hydrogen are temporally separated; that is, oxygen evolves in a first stage and hydrogen evolves in a second stage.

The two enzyme and pathway options result in four photobiological hydrogen production processes:

- direct biophotolysis using hydrogenase
- direct biophotolysis using nitrogenase
- indirect biophotolysis using hydrogenase
- indirect biophotolysis using nitrogenase

The use of nitrogenase is more energy intensive and therefore less efficient than pathways using hydrogenase [19].

The main energy input to these processes is solar energy. It is assumed that water is readily available and requires negligible processing energy.

3.1.4. Gasification

Gasification is a process by which organic or fossil-based materials are reacted at high temperatures, without combustion, and with a controlled amount of air, oxygen, and/or steam. Synthesis gas (or syngas) is ultimately produced, which is a mixture of carbon monoxide, carbon dioxide, and hydrogen. Syngas can then undergo a water–gas shift reaction in order to produce hydrogen, as follows:

$$CO + H_2O \rightarrow CO_2 + H_2$$

Hydrogen is then isolated using a separation technique, such as pressure swing adsorption.

Two gasification processes are investigated: coal gasification and biomass gasification.

3.1.4.1. Coal gasification. Coal gasification is one of the oldest fossil fuel-based methods for hydrogen production. Coal is heated in a restricted supply of air (a process known as destructive distillation or pyrolysis), resulting in a mixture of H_2, CH_4, and CO, together with tar and coke [20]. Alternatively, heated coal can also be reacted with steam to produce syngas. Subsequent separation techniques are then applied, yielding hydrogen gas [20].

The main energy input to this process is coal. The study by Rand and Dell in Ref. [20] is applied in this investigation. Pittsburgh no. 8 bituminous coal is used in a central, large-scale facility. It is assumed that the substitution of other coal types does not affect system efficiency.

3.1.4.2. Biomass gasification. Biomass gasification is the most widely utilized process for biomass to hydrogen gas conversion, as it has a high process efficiency compared to other thermal biomass conversion methods [21,22].

The main energy inputs to this process are biomass, natural gas, and electricity. In this study, woody biomass is used with a final moisture content between 5 and 17.5 wt% [22]. Electricity is required for gasification and natural gas is required by the steam reformer for burner control.

3.1.5. Steam reforming

Steam reforming of hydrocarbons is the most efficient, economical, and widely used process for the production of hydrogen [23]. A processing device, known as a reformer, is used to react steam with fuel at high temperatures in order to produce hydrogen.

Two steam reforming methods are investigated in this study: steam methane reforming and steam ethanol reforming.

3.1.5.1. Steam methane reforming. Approximately 90% of hydrogen today is produced from fossil fuels, mainly through steam methane reforming [22]. Natural gas, consisting primarily of methane, is commonly used as the main feed. Electricity is also required for the compression, storage, and dispensing of hydrogen gas [23].

3.1.5.2. Steam ethanol reforming. Steam reforming can also be performed using ethanol (C_2H_5OH) as a fuel source. The main energy inputs to this process are ethanol and electricity. Ethanol can be produced either as a petrochemical through the hydration of ethylene, or biologically through fermentation using yeast [24]. The biological production of ethanol using wood chips is assumed in this study.

3.1.6. Partial oxidation

Partial oxidation is a process by which a fuel–air mixture is partially combusted in a reformer vessel, resulting in syngas. Several primary energy sources can be used for fuel, including natural gas, coal, biomass, petroleum coke, and oil [25]. Non-catalytic partial oxidation is investigated using natural gas as a fuel source; the experimental results by Rabe et al. in Ref. [26] are referenced.

The syngas resulting from partial oxidation is subject to the water–gas shift reaction in order to generate more hydrogen. A separation technique can then be applied to isolate hydrogen gas.

Partial oxidation results in a higher hydrogen production rate compared to steam reforming [25]; however, one drawback of the process is that it requires the use of expensive oxygen (as opposed to air) [20].

The main energy input to this process is natural gas. H_2O is assumed to be readily available and requires negligible processing energy. O_2 is not included in the system boundaries.

3.2. Electricity mixes

The compositions of the Swiss production, Swiss consumer, and Union for the Coordination of the Transmission of Electricity (UCTE) electricity mixes are given in Table 1 below [27,28].

4. Methodology

4.1. Framework

The general framework of the study is outlined in the following subsections.

Table 1
Composition of electricity mixes.

	CH production mix (%)	CH consumer mix (%)	UCTE mix (%)
Fossil fuels (coal, oil, natural gas)	3.1	2.2	51.1
Nuclear power	38.0	41.1	31.6
Hydropower	56.6	33.8	12.7
Other renewables	0.3	0.1	3.1
Waste incineration	2.1	2.0	1.4
Unverified[a]	0.0	20.7	0.0

[a] Unverified sources due to electricity trading.

4.1.1. Hydrogen production & Electricity generation pathways

The hydrogen and electricity production pathways to be investigated are listed in Table 2. A wide range of processes are analyzed, including well-established pathways in an international context. These pathways are relevant given the energy trading potential between Switzerland and surrounding European countries. They also enable an international comparison.

4.1.2. Drivetrains and energy carriers

Internal combustion engine, battery-electric, fuel cell, and hybrid-electric drivetrains are evaluated. Table 3 details each drivetrain and energy carrier under investigation.

The term pluggable electric vehicle (PEV) refers to EV and plug-in hybrid vehicles.

4.1.3. Reference vehicle

A base reference vehicle is defined for this study. Base vehicle characteristics and assumptions are given in Table 4.

The reference vehicle is used as the basis for determining all drivetrain energy carrier consumption rates, as detailed in Section 4.2.4.

4.2. Calculations

Fig. 3 below illustrates the primary energy demand chain for a drivetrain from resource extraction to vehicle propulsion.

Section labels in Fig. 3 correspond to the section numbers detailing the respective calculation steps.

Primary energy demand and GHG emissions account for all upstream process losses with one exception: the gray energy and gray emissions associated with hydrogen production plant construction, maintenance, and disposal have been neglected due to a lack of available data for relatively novel production methods. The resulting implication is that PE demand and GHG emissions factors for hydrogen production processes underestimate true values. However, the gray energy and emissions associated with all energy carrier inputs have been considered.

4.2.1. Primary energy demand and GHG emissions for secondary energy production

The primary energy demand and GHG emissions for secondary energy production have been calculated by ESU-services Ltd. in a study based on the Swiss Centre for LifeCycle Inventories' ecoinvent database [31]. The ecoinvent database applies lifecycle assessment

Table 2
Energy carrier production pathways.

Hydrogen production process	Electricity source
1. Low temperature electrolysis	1. Nuclear power
2. High temperature electrolysis	2. Combined cycle plant (CCP) using natural gas
3. Solar thermochemical dissociation of ZnO via solar thermal dissociation	3. Coal power plant (steam)
4. Direct and indirect photobiological splitting using the enzyme hydrogenase or nitrogenase	4. Oil power plant
5. Coal gasification	5. Waste incineration
6. Biomass gasification	6. Combined heat and power plant (CHP) using wood
7. Steam methane reforming	7. CHP using diesel
8. Steam ethanol reforming	8. CHP using natural gas
9. Partial oxidation	9. CHP using biogas (from organic waste and sewage sludge fermentation)
	10. Wind power
	11. Photovoltaic power
	12. Hydropower
	13. Pumped storage
	14. Swiss (CH) production mix
	15. CH consumer mix
	16. Union for the Coordination of the Transmission of Electricity (UCTE) mix

Table 3
Vehicle drivetrain definitions.

Abbreviation	Drivetrain definition
$ICEV_{Gas}$	Gasoline internal combustion engine vehicle Energy carrier: gasoline
$ICEV_{Dies}$	Diesel internal combustion engine vehicle Energy carrier: diesel
$ICEV_{CNG}$	Compressed natural gas (CNG) internal combustion engine vehicle Energy carrier: compressed natural gas
$ICEV_{Bio}$	Compressed biogas internal combustion engine vehicle Energy carrier: biogas
EV	Full electric vehicle using a lithium ion (Li-ion) battery-driven electric motor Energy carrier: electricity
FCV	Proton exchange membrane fuel cell vehicle using a fuel cell-driven electric motor Energy carrier: hydrogen
HEV_{Gas}	Full hybrid vehicle using a gasoline internal combustion engine and Li-ion battery-driven electric motor Energy carrier: gasoline
HEV_{CNG}	Full hybrid vehicle using a CNG internal combustion engine and Li-ion battery-driven electric motor Energy carrier: CNG
HEV_{Bio}	Full hybrid vehicle using a compressed biogas internal combustion engine and Li-ion battery-driven electric motor Energy carrier: biogas
PH-$ICEV_{Gas}$	Plug-in-hybrid vehicle using a gasoline ICE and electric motor with Li-ion battery Energy carrier: gasoline and electricity
PH-FCV	Plug-in-hybrid vehicle using a fuel cell-driven electric motor and Li-ion battery Energy carrier: hydrogen and electricity

(LCA) analyses according to International Organisation for Standardisation (ISO) guidelines in Refs. [32,33].

The following assumptions have been made in this study regarding secondary energy inputs.

4.2.1.1. *Methane.*

Methane is not explicitly defined in Ref. [31]. However, natural gas consists of approximately 90% methane and is therefore assumed as the methane source in this study [34].

4.2.1.2. *Ethanol.*

Ethanol is assumed to derive from the fermentation of biomass (wood chips) in this study. The ethanol production process is assumed to have an efficiency of 28.12% according to Ref. [35]. By applying this efficiency to the primary energy factor for wood chips (1.14 MJ_{PE}/MJ), the primary energy factor for the production of ethanol can be estimated as:

$$PE_{ethanol} = \frac{1.14}{0.2812} = 4.05\frac{MJ_{PE}}{MJ_{ethanol}}$$

Gray energy for ethanol production has not been taken into consideration; hence, this value slightly underestimates the true primary energy factor.

Table 4
Reference vehicle definition.

Base vehicle mass including powertrain (excluding addition of battery/fuel cell system):	1350 kg
Equivalent ICE power:	70 kW
Manufacturing year:	2010
Battery-electric range for plug-in hybrid vehicles:	60 km
Electric range for full battery-electric and fuel cell vehicles:	180 km
Li-ion battery specific energy density:	150 Wh kg^{-1} [29]
Fuel cell specific weight:	3 kg kW^{-1} [30]
Total distance driven by a vehicle in its lifetime:	150 000 km

Greenhouse gas emissions for the production of ethanol are estimated as 0.039 kg CO_2-eq/MJ, which includes emissions due to fermentation. This figure is based on the lifecycle study in Ref. [35].

4.2.1.3. *Biomass.*

Given the abundance of wood resources in Switzerland, biomass is assumed to be wood log, wood chips, or pellets in this study. Pellets are composed of compressed organic material.

4.2.1.4. *Biogas.*

Biogas is derived from organic waste fermentation (48%) and sewage sludge fermentation in waste water treatment plants (52%) [36].

4.2.1.5. *Process heat from solar energy.*

Process heat from solar energy is assumed to derive from concentrated solar power (CSP). However, primary energy and GHG emission values are not available for CSP in the ecoinvent database. It is assumed that CSP plants share the same PE demand and GHG emissions factors as wind power plants.

4.2.1.6. *Non-solar energy process heat.*

It is assumed that non-solar process heat energy inputs derive from nuclear power stations.

4.2.1.7. *Combined heat and power (CHP) plants – electricity and heat emissions and energy burden.*

As CHP plants simultaneously produce electricity and heat, an allocation method must be selected in order to attribute shares of the total GHG emissions and PE demand to each output. In Ref. [31], the PE demand and GHG emissions for electricity and heat from CHP plants is determined by applying an exergy content-based allocation method. Since electricity has a higher exergetic value than heat, electricity bears an over-proportional share of the energy and emissions burden in this approach. In the case of a natural gas CHP plant, for example, the burden can be calculated as approximately 76% on electricity and 24% on heat (based on a CHP electric efficiency of 33% and heat efficiency of 52% [36]). This study employs the exergy-based approach; however, a range of allocation methods are possible.

In a heat-driven allocation approach, an over-proportional share of the energy and emissions burden is placed on heat instead of electricity. The heat burden is determined according to the input energy required by a conventional boiler to produce the same amount of heat as a CHP plant using one unit of input energy. Assuming a boiler efficiency of 95%, the heat burden is approximately 55% and the electricity burden is 45%.

As an illustrative example, results will be provided for both allocation methods: the exergy-based (electricity-driven) approach and the heat-driven approach.

4.2.2. *Hydrogen production process efficiency*

The hydrogen production process efficiency is calculated according to:

$$\eta_{H2} = \frac{\dot{E}_{H2}}{\sum_{i=1}^{n}\dot{E}_i}$$

where:

η_{H2} is the efficiency of the hydrogen production process
$\dot{E}_{H2}$ is the rate of hydrogen production (units of energy per cycle, time, or mass unit)
$\dot{E}_i$ is an energy input to the production process (same units as)
η is the number of energy inputs to the process

A heliostat efficiency of 64% is assumed for solar energy process heat inputs.

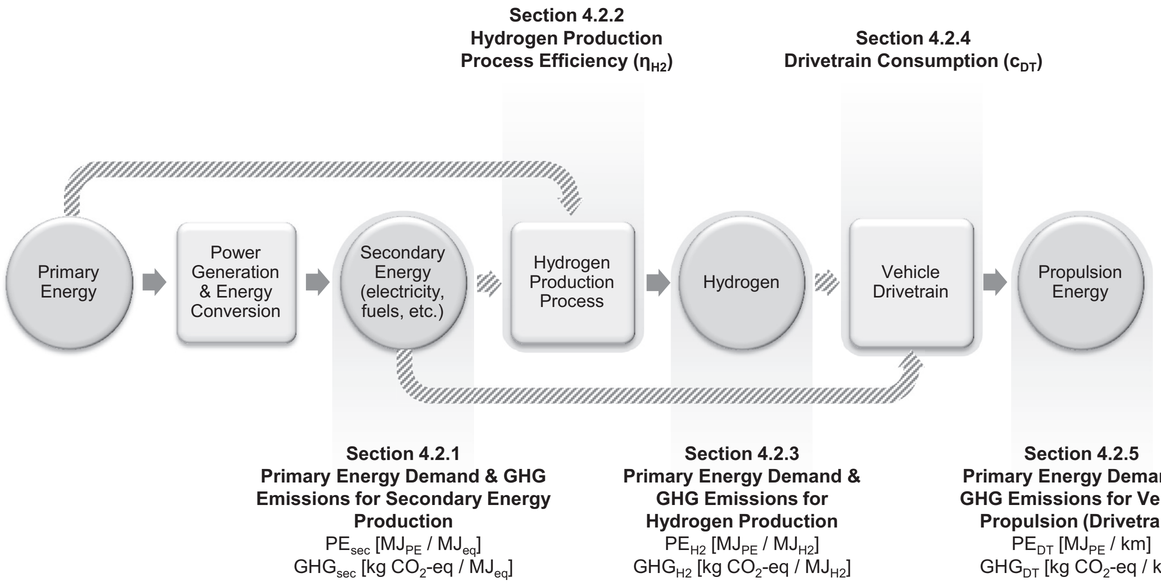


Fig. 3. PE demand and GHG emissions flow diagram for vehicle drivetrains from resource extraction to vehicle propulsion; lightly shaded energy flows do not apply in all cases.

4.2.3. *Primary energy demand and GHG emissions for hydrogen production*

The primary energy demand for a given hydrogen production process is determined using the following relationship:

$$PE_{H2} = \sum_{i=1}^{n} \frac{W_i PE_{sec,i}}{\eta_{H2}}$$

where:

PE_{H2} is the primary energy demand for the hydrogen production process (MJ_{PE}/MJ_{H2})
$PE_{sec,i}$ is the primary energy demand for the secondary energy input i (MJ_{PE}/MJ_{sec})
W_i is the weight of input i, as a fraction of the total input energy. That is:

$$W_i = \frac{\dot{E}_i}{\sum_{j=1}^{n} \dot{E}_j}$$

Analogously, the greenhouse gas emissions for the given hydrogen production process is given by:

$$GHG_{H2} = \sum_{i=1}^{n} \frac{W_i GHG_{sec,i}}{\eta_{H2}}$$

where:

GHG_{H2} is the greenhouse gas emission for the hydrogen production process (kg CO_2-eq/MJ_{H2})
$GHG_{sec,i}$ is the greenhouse gas emission for the secondary energy input i (kg CO_2-eq/MJ_{sec})

The source of electricity is assumed to be the Swiss production mix for all non-electrolysis hydrogen production processes which require electricity as an input. (Electricity accounts for less than 5% of the total energy input in these cases.) Several electricity sources are investigated for electrolysis processes.

Once again, it is noted that not all gray energy associated with hydrogen production processes has been accounted for (e.g., for plant construction and maintenance). Hence, this calculation underestimates the true primary energy and GHG emission factors for hydrogen production.

4.2.4. *Energy carrier consumption rates of drivetrains*

The gasoline ICE drivetrain consumption rate is approximated using manufacturer specifications for the reference vehicle, which are calculated according to the EU automotive directive 80/1268/EEC, “Fuel Consumption of Motor Vehicles” [37].

Appropriate relative performance factors are applied to the base consumption rate according to Ref. [38] in order to determine alternative drivetrain consumption rates. The structural mass increase due to the battery and/or fuel cell system is accounted for. All vehicles maintain equal power to mass ratios in order to guarantee comparable performance across drivetrains.

The electric share (ES) of a plug-in hybrid vehicle refers to the ratio of the distance driven electrically to the total distance traveled by a vehicle in its lifetime. It is based on the all-electric range (AER) of the battery and on the distribution of trip lengths made by the vehicle. For an AER of 60 km, the electric share is assumed to be 46% [39].

Drivetrain consumption rate estimations vary according to driving cycles and vehicle designs, but these variations are not critical to overall trends and relative behaviors.

4.2.5. *Primary energy demand and GHG emissions for vehicle propulsion*

The WTW primary energy demand and GHG emissions for each vehicle drivetrain can be determined using the following equation:

$$PE_{DT} = \sum_{i=1}^{m} PE_i C_i$$

where:

PE_{DT} is the primary energy demand for the given vehicle drivetrain (MJ_{PE}/km)
PE_i is the primary energy demand for energy carrier i (this can be PE_{sec} or PE_{H2},depending on the drivetrain) ($MJ_{PE}/MJ_{energy\_carrier}$)

C_i is the final energy carrier consumption rate for drivetrain i ($\mathrm{MJ}_{\mathrm{energy\_carrier}}/\mathrm{km}$)
m is the number of vehicle drivetrains

Analogously, the GHG emissions can be calculated as:

$$\mathrm{GHG}_{\mathrm{DT}} = \sum_{i=1}^{m} \mathrm{GHG}_i C_i$$

5. Hydrogen production process efficiencies and drivetrain consumption rates

Hydrogen production process efficiencies and drivetrain energy carrier consumption rates serve as key inputs for further calculations. These values are detailed in the following subsections.

5.1. Hydrogen production process efficiencies

The input data and efficiency for each hydrogen production process are summarized in Table 5.

The above technology efficiencies are largely based on US studies, however, it is assumed that technology variations in the Swiss context are negligible. Efficiency values are also assumed to be representative estimations, although variations exist depending on the specific process setup. These variations are not expected to impact relative trends.

5.2. Drivetrain consumption rates

Drivetrain energy carrier consumption rates are calculated based on the reference vehicle and are presented in Table 6.

Both absolute and normalized consumption rates are given. Consumption rates are normalized relative to the $\mathrm{ICEV}_{\mathrm{Gas}}$. The electric share for plug-in hybrid vehicles is also represented.

The total vehicle mass and power for each vehicle (maintaining the same mass to power ratio) is presented in Table 7.

6. Results & discussion

Hydrogen production PE demand and GHG emissions are presented first, followed by drivetrain well-to-wheel PE demand and GHG emissions.

6.1. Hydrogen production processes primary energy demand and GHG emissions

Fig. 4 illustrates the PE demand and GHG emissions for hydrogen production processes only.

6.1.1. Renewable and non-renewable energy resources

Electrolysis processes using coal, oil, and diesel fossil fuels exhibit the highest GHG emissions. The corresponding primary energy demand is also relatively high compared to other processes. Steam methane reforming and partial oxidation using natural gas demonstrate the lowest GHG emissions and primary energy demand amongst fossil fuel resources.

All renewable energy-based hydrogen production processes exhibit relatively low GHG emissions. However, the primary energy demand for these processes varies significantly depending on the process and secondary energy source.

6.1.2. Direct and indirect chemical conversion processes for hydrogen production

A distinction is made between direct and indirect chemical conversion processes for hydrogen production. Indirect processes

Table 5
Hydrogen production process efficiencies according to sources indicated; input shares shown as percentage of total in brackets.

Hydrogen production process		Process input							Hydrogen output	Process efficiency
		Electricity	Heat (nuclear)	Solar energy	Natural gas (methane)	Coal (carbon)	Biomass	Ethanol		
Electrolysis	Low temperature electrolysis [14]	0.192 $\mathrm{GJ/kg_{H2}}$[a] (100%)							0.12 $\mathrm{GJ/kg_{H2}}$[b]	62.5%
	High temperature electrolysis [15]	0.119 $\mathrm{GJ/kg_{H2}}$[e] (83%)	0.025 $\mathrm{GJ/kg_{H2}}$ (17%)						0.12 $\mathrm{GJ/kg_{H2}}$[d]	83.3%
Thermochemical dissociation [40]	Solar thermal dissociation	7439 GJ/a (2%)		346,984 GJ/a (98%)					100,300 GJ/a[c]	28.3%
Photobiological splitting [19]	Direct-hydrogenase			1408 kJ (100%)					572.5 kJ	40.7%
	Direct-nitrogenase			2816 kJ (100%)					572.5 kJ	20.3%
	Indirect-hydrogenase			2112 kJ (100%)					572.5 kJ	27.1%
	Indirect-nitrogenase			3520 kJ (100%)					572.5 kJ	16.3%
Gasification	Coal gasification [23]					0.271 $\mathrm{GJ/kg_{H2}}$[c,d] (100%)			0.12 $\mathrm{GJ/kg_{H2}}$[d]	44.3%
	Biomass gasification [41]	0.006 $\mathrm{GJ/kg_{H2}}$ (2%)			0.006 $\mathrm{GJ/kg_{H2}}$[d] (2%)		0.251 $\mathrm{GJ/kg_{H2}}$[c,d] (96%)		0.12 $\mathrm{GJ/kg_{H2}}$[d]	45.6%
Steam reforming	Steam methane reforming [42]	0.002 $\mathrm{GJ/kg_{H2}}$ (1%)			0.165 $\mathrm{GJ/kg_{H2}}$[d] (99%)				0.12 $\mathrm{GJ/kg_{H2}}$[d]	71.9%
	Steam ethanol reforming [43]	0.009 $\mathrm{GJ/kg_{H2}}$ (5%)						0.176 $\mathrm{GJ/kg_{H2}}$[c,d] (95%)	0.12 $\mathrm{GJ/kg_{H2}}$[d]	64.9%
Partial oxidation [26]					0.804 $\mathrm{MJ/kg_{H2}}$[d] (100%)				0.721 $\mathrm{MJ/kg_{H2}}$[d,d]	89.7%
					0.804 $\mathrm{MJ/kg_{H2}}$[d] (100%)				0.438 $\mathrm{MJ/kg_{H2}}$[e,d]	54.5%

[a] Current value based on 2005 study.
[b] Based on lower heating value (LHV) of hydrogen.
[c] Based on higher heating value (HHV).
[d] Output based on the assumption of 100% reactant conversion.
[e] Output based on the assumption of 60.8% reactant conversion.

Table 6
Tank-to-wheel drivetrain consumption ratios based on reference vehicle.

Vehicle	Drivetrain consumption by energy carrier (MJ/km)			Electric share	Total consumption (MJ/km)	Total consumption (normalized)
	Gasoline, diesel, CNG or biogas	Electricity[a]	Hydrogen			
$\mathrm{ICEV}_{\mathrm{Gas/CNG/Bio}}$	1.71				1.71	1.00
$\mathrm{ICEV}_{\mathrm{Dies}}$	1.41				1.41	0.82
$\mathrm{HEV}_{\mathrm{Gas/CNG/Bio}}$	1.19				1.19	0.69
EV		0.62			0.62	0.36
FCV			0.97		0.97	0.57
$\mathrm{PH\text{-}ICEV}_{\mathrm{Gas}}$	0.67	0.26		46%	0.93	0.54
PH-FCV		0.33	0.56	46%	0.89	0.52

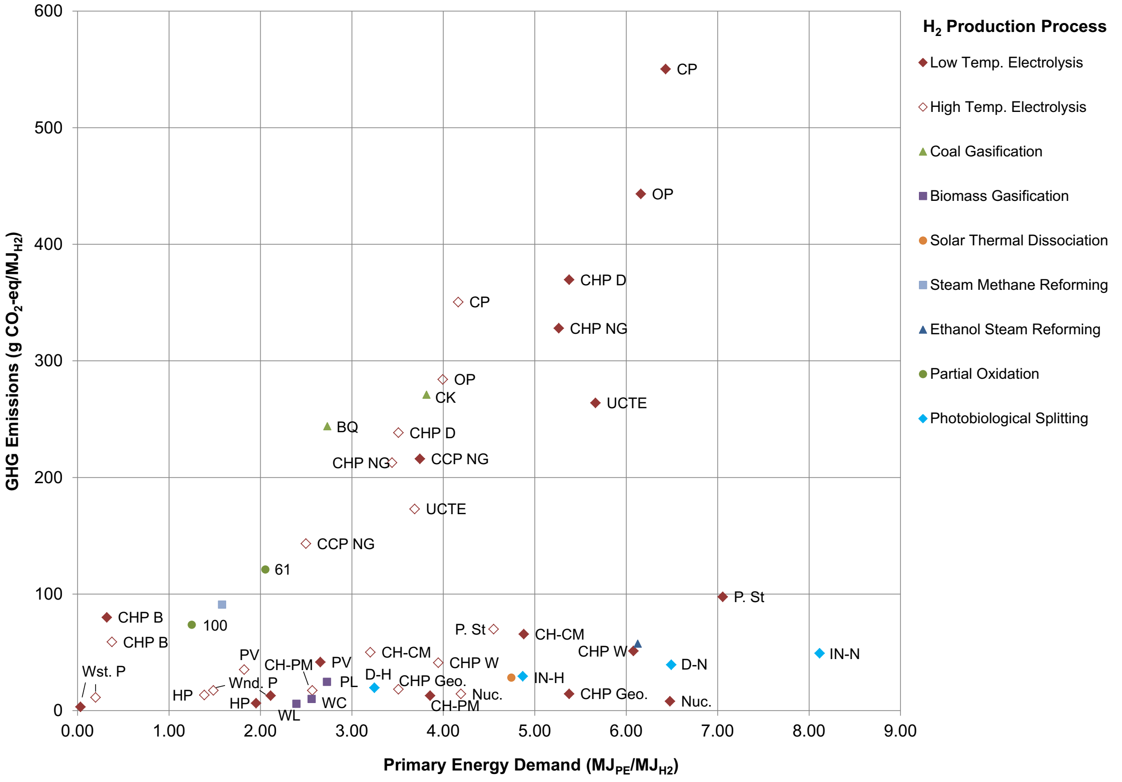
[a] Charging and discharging efficiencies have been considered for battery-electric vehicles.

Table 7
Drivetrain mass and power.

Vehicle	Mass (kg)	Power (kW)
$\mathrm{ICEV}_{\mathrm{Dies}}$	1350	70
$\mathrm{HEV}_{\mathrm{Gas/CNG/Bio}}$	1389	72
EV	1634	85
FCV	1771	92
$\mathrm{PH\text{-}ICEV}_{\mathrm{Gas}}$	1461	76
PH-FCV	1881	98

involve secondary energy conversion, such as electricity conversion during electrolysis, while direct processes involve primary energy conversion, such as natural gas conversion during steam methane reforming.

The lowest PE demand and GHG emissions are observed for electrolysis using electricity from waste incineration, biogas CHP, hydropower, wind power, and photovoltaic power. Waste is essentially emission and energy demand-free because the majority of the GHG emissions and PE demand have been accounted for in an upstream process.



Energy Source and/or Process Technology

BQ.:	Coal – Briquette
CCP NG:	Combined Cycle Plant (CCP) Natural Gas
CH-CM:	Swiss Consumer Mix
CH-PM:	Swiss Production Mix
CHP B:	CHP – Biogas
CHP D:	CHP – Diesel
CHP Geo.:	CHP – Geothermal Energy
CHP NG:	CHP – Natural Gas
CHP W:	Combined Heat and Power Plant (CHP) – Wood
CK:	Coal – Coke
CP:	Coal Power Plant
D-H:	Direct - Hydrogenase
D-N:	Direct - Nitrogenase
HP:	Hydropower
IN-H:	Indirect - Hydrogenase
IN-N:	Indirect - Nitrogenase
Nuc.:	Nuclear Power Plant
OP:	Oil Power Plant
P St.:	Pumped Storage
PL:	Pellets
PV:	Photovoltaic
UCTE:	Union for the Coordination of the Transmission of Electricity (UCTE) Mix
WCH:	Wood Chips
WL:	Wood Log
Wnd. P:	Wind Power
Wst. P:	Waste Power Plant
61:	Assuming 61% reactant conversion
100:	Assuming 100% reactant conversion

Fig. 4. PE demand and GHG emissions for H_2 production processes; symbols indicate production process; abbreviations indicate energy source and/or process technology.

Of the renewable, direct chemical conversion processes for hydrogen production, biomass gasification and direct photobiological splitting using hydrogenase result in the lowest GHG emissions and PE demand.

The primary energy demand for photobiological splitting varies significantly depending on the specific approach and enzyme. Indirect photobiological splitting using nitrogenase demonstrates the second highest primary energy demand, while direct photobiological splitting using hydrogenase is on par with the PE demand and GHG emissions of biomass gasification.

6.1.3. *Overall*

Process performance is highly dependent on the secondary energy source utilized. This is especially apparent in the case of electrolysis. The electricity source or mix plays a critical role in energy demand and emissions performance.

6.2. *Drivetrain WTW primary energy demand and GHG emissions*

Well-to-wheel primary energy demand and GHG emissions are presented for direct and indirect electricity conversion pathways, followed by direct chemical conversion pathways only.

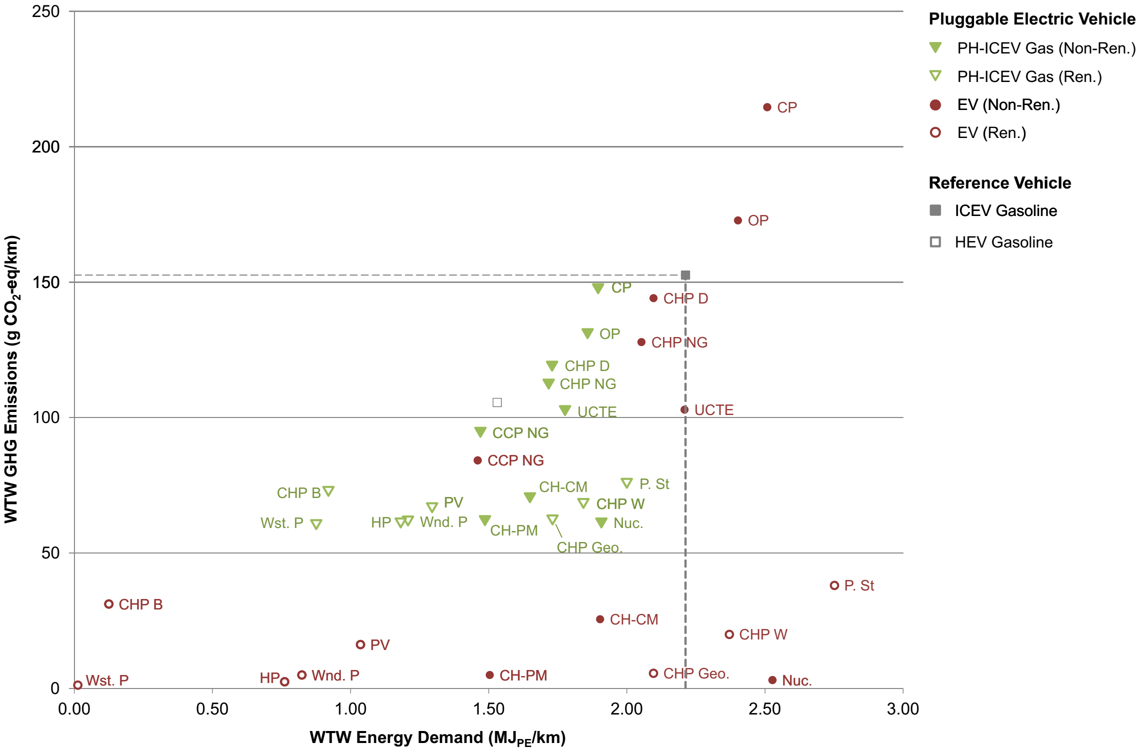
Direct electricity conversion pathways refer to PEV electrification. Indirect electricity conversion pathways refer to hydrogen production via electrolysis for FCVs.

6.2.1. *Direct and indirect electricity conversion pathways*

6.2.1.1. PEV electrification. Fig. 5 compares the WTW energy demand and GHG emissions for EVs and PH-ICEVs using different electricity sources. Distinct markers differentiate between renewable and non-renewable energy resources. The ICEV$_{Gas}$ and HEV$_{Gas}$ are given as reference points.

6.2.1.2. Critical electricity mixes. The spread of PH-ICEV WTW values is small compared to EVs due to gasoline usage in Fig. 5. The electric share (46%) dictates the degree of electrification and range of values. For a given electric share, a critical electricity mix can be defined where EV and PH-ICEV$_{Gas}$ WTW energy demand and GHG emissions are equal; this mix defines a boundary condition between EV and PH-ICEV$_{Gas}$ performance. EVs outperform PH-ICEVs (and PH-ICEVs outperform EVs) where the electricity source has lower (higher) PE demand and GHG emissions factors than the critical mix. In Fig. 5, this mix has a PE demand factor of 2.36 MJ$_{PE}$/MJ$_{elec}$ and GHG emissions factor of 163 g CO$_2$-eq/MJ$_{elec}$. This corresponds to a mix with approximately the same PE demand and GHG emissions factors as the Swiss production mix (CH-PM) and UCTE mix, respectively.

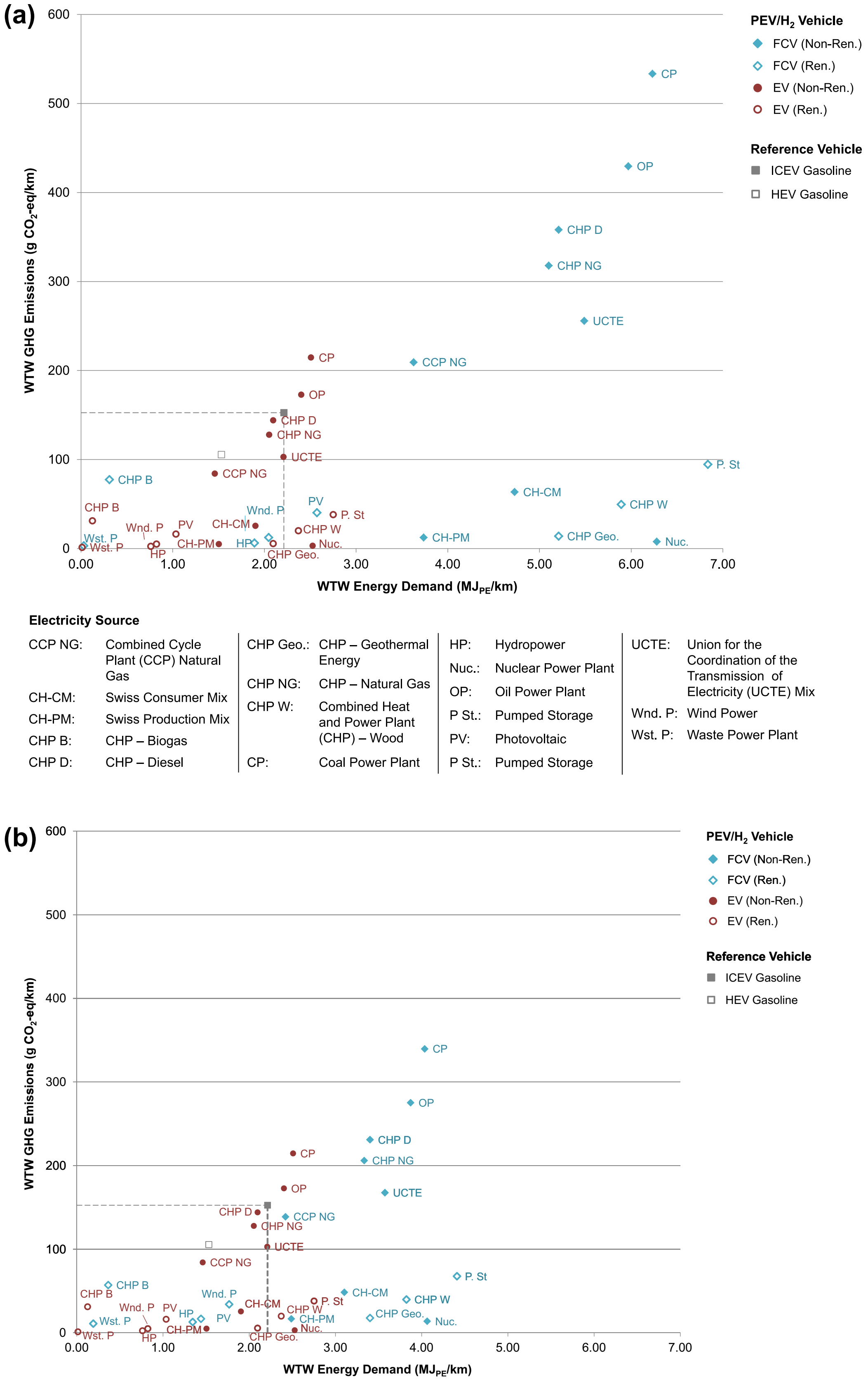
Similarly, an electricity mix can also be identified which divides optimal performance between the ICEV$_{Gas}$ and EV. In Fig. 5, this theoretical mix has a PE demand factor of 3.55 MJ$_{PE}$/MJ$_{elec}$ and GHG emissions factor of 245 kg CO$_2$-eq/MJ$_{elec}$.



Electricity Source

CCP NG:	Combined Cycle Plant (CCP) Natural Gas
CH-CM:	Swiss Consumer Mix
CH-PM:	Swiss Production Mix
CHP B:	CHP – Biogas
CHP D:	CHP – Diesel
CHP Geo.:	CHP – Geothermal Energy
CHP NG:	CHP – Natural Gas
CHP W:	Combined Heat and Power Plant (CHP) – Wood
CP:	Coal Power Plant
HP:	Hydropower
Nuc.:	Nuclear Power Plant
OP:	Oil Power Plant
P St.:	Pumped Storage
PV:	Photovoltaic
P St.:	Pumped Storage
UCTE:	Union for the Coordination of the Transmission of Electricity (UCTE) Mix
Wnd. P:	Wind Power
Wst. P:	Waste Power Plant

Fig. 5. WTW energy demand and GHG emissions for EV and PH-ICEV drivetrains for various electricity sources based on reference vehicle characteristics; hollow markers indicate renewable energy source; solid markers indicate non-renewable energy source.



Electricity Source

CCP NG:	Combined Cycle Plant (CCP) Natural Gas
CH-CM:	Swiss Consumer Mix
CH-PM:	Swiss Production Mix
CHP B:	CHP – Biogas
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OP:	Oil Power Plant
P St.:	Pumped Storage
PV:	Photovoltaic
P St.:	Pumped Storage
UCTE:	Union for the Coordination of the Transmission of Electricity (UCTE) Mix
Wnd. P:	Wind Power
Wst. P:	Waste Power Plant

Fig. 6. WTW energy demand and GHG emissions for EV and FCV drivetrains for various electricity sources based on reference vehicle characteristics; hollow markers indicate renewable energy source; solid markers indicate non-renewable energy source. (a): hydrogen production via low temperature electrolysis. (b): hydrogen production via high temperature electrolysis.

Again, it is evident that the electricity mix plays a critical role in defining the optimal drivetrain strategy to minimize WTW GHG emissions and/or energy demand.

6.2.1.3. Renewable vs. non-renewable energy resources. All renewable energy pathways (hollow markers in Fig. 5) demonstrate low WTW GHG emissions. The EV results in lower WTW GHG emissions than the PH-ICEV for all renewable energy electricity sources.

In accordance with observations in Fig. 4, the largest reduction in GHG emissions and PE demand are observed for electricity from waste incineration, biogas CHP, hydropower, wind power, and photovoltaic power. Of the non-renewable resource pathways evaluated, only natural gas and nuclear energy result in a remarkable reduction in WTW GHG emissions compared to the ICEV_{Gas}. Of the three electricity mixes considered, the Swiss mixes have the lowest energy demand and GHG emissions.

6.2.1.4. EV vs. FCV performance. EV and FCV performance is compared next in Fig. 6a. Hydrogen is produced via low temperature electrolysis. Dashed reference lines illustrate ICEV_{Gas} WTW energy demand and GHG emissions.

The FCV has higher WTW energy demand and GHG emissions compared to the EV due to a lower overall energy conversion efficiency chain. The drivetrain efficiency of the FCV is lower than the EV and hydrogen production via electrolysis introduces additional losses through electricity conversion. Hence, FCVs using electrolysis are considerably more sensitive to variations in the electricity mix than EVs.

An improvement upon the results in Fig. 6a would be given by a higher efficiency electrolysis process; namely, high temperature electrolysis. Fig. 6b illustrates this case. Relatively low WTW energy demand and GHG emissions are given by the five aforementioned renewable energy electricity sources.

6.2.2. Direct chemical conversion pathways

FCVs are unable to compete with EV WTW energy demand and GHG emissions via electricity pathways due to a lower overall energy conversion efficiency chain. However, direct chemical conversion pathways for hydrogen production offer efficiency gains with the potential to bridge the gap between EV and FCV WTW performance.

Direct chemical conversion pathways are presented according to natural resource category. This approach enables a comparison of WTW pathways based on the same primary energy resource. Such information provides valuable insight into optimal resource allocation problems in the context of primary energy demand and GHG emissions.

The natural resource categories are coal, natural gas, biomass, and solar energy. These categories were selected as they provide coverage of both conventional hydrogen production methods (e.g., coal gasification) and novel production processes (e.g., photobiological splitting).

ICEV and HEV drivetrains using CNG, biogas, and diesel are introduced as additional reference vehicles in the following results. PH-FCVs are also included.

6.2.2.1. Coal. Fig. 7 depicts WTW results for direct coal energy conversion pathways. Electricity is generated via a coal power plant and hydrogen is produced via coal gasification. These pathways represent conventional and internationally-relevant means for electricity generation and hydrogen production.

Alternative drivetrains based on coal energy produce higher WTW results than the ICEV_{Gas} due to the relatively high energy demand and GHG emission intensity of coal compared to gasoline. Only the $\text{PH-ICEV}_{\text{Gas}}$, with its higher drivetrain efficiency, yields lower WTW results compared to the ICEV_{Gas}.

The alternative fuel ICEVs and HEVs introduced in Fig. 7 yield significantly reduced WTW energy demand and GHG emissions

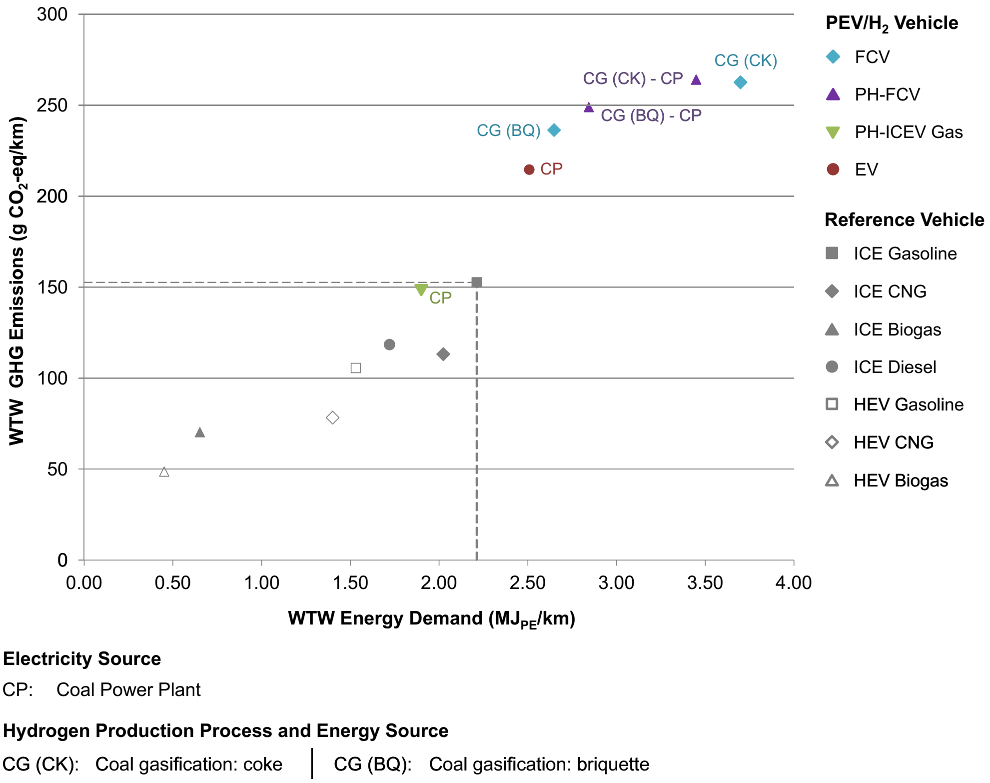

Fig. 7. WTW energy demand and GHG emissions via direct coal energy conversion pathways for drivetrains based on reference vehicle characteristics.

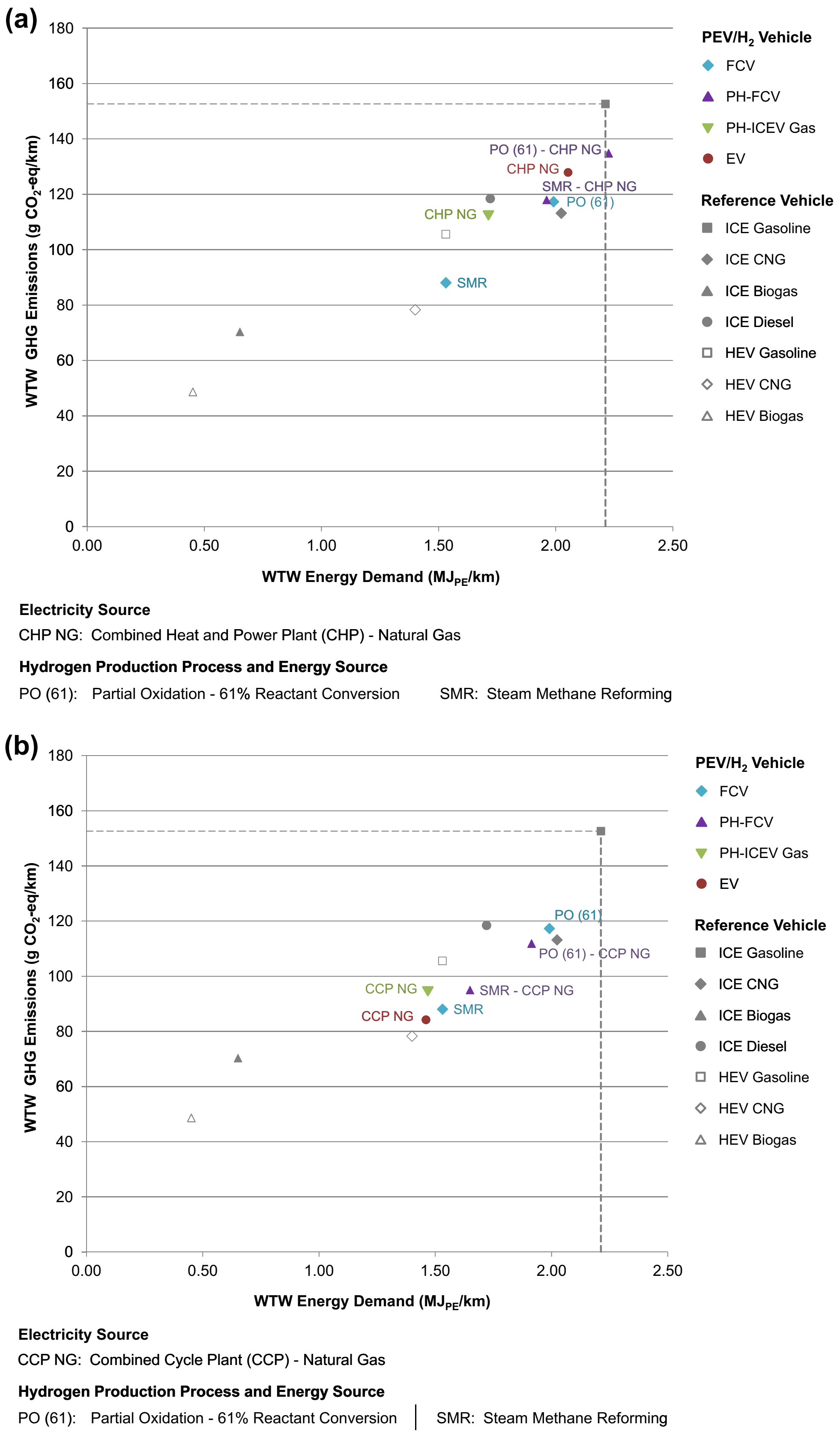

Fig. 8. WTW energy demand and GHG emissions via direct natural gas conversion pathways for drivetrains based on reference vehicle characteristics. (a): electricity generation via CHP; exergy-based CHP burden allocation. (b): electricity generation via CCP.

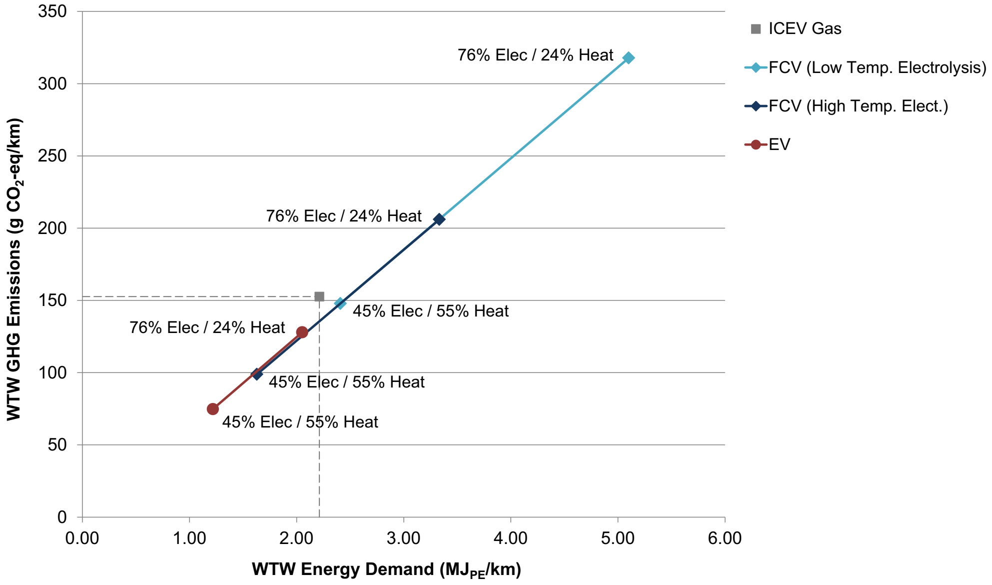

Fig. 9. WTW Energy demand and GHG emissions – comparison of burden Allocation methods for natural gas CHP: exergy-based (76% electricity/24% heat) vs. heat burden (45% electricity/55% heat).

compared to the coal-based pathways. The $ICEV_{Bio}$ and HEV_{Bio}, for instance, demonstrate WTW energy demand and GHG emission reductions of over 50% compared to the $ICEV_{Gas}$. The HEV_{CNG} also yields relatively low WTW results.

The performance of PH-FCVs is dictated by EV and FCV characteristics. However, the PH-FCV mass is higher than the FCV and EV, which results in comparatively high hydrogen and electricity consumption rates. Therefore, PH-FCV WTW performance exceeds or lies in between EV and FCV results, depending on the primary energy demand and GHG emissions of the electricity and hydrogen production process.

6.2.2.2. Natural gas. Natural gas pathways are presented in Fig. 8a and b for electricity generation via natural gas CHP and CCP plants,

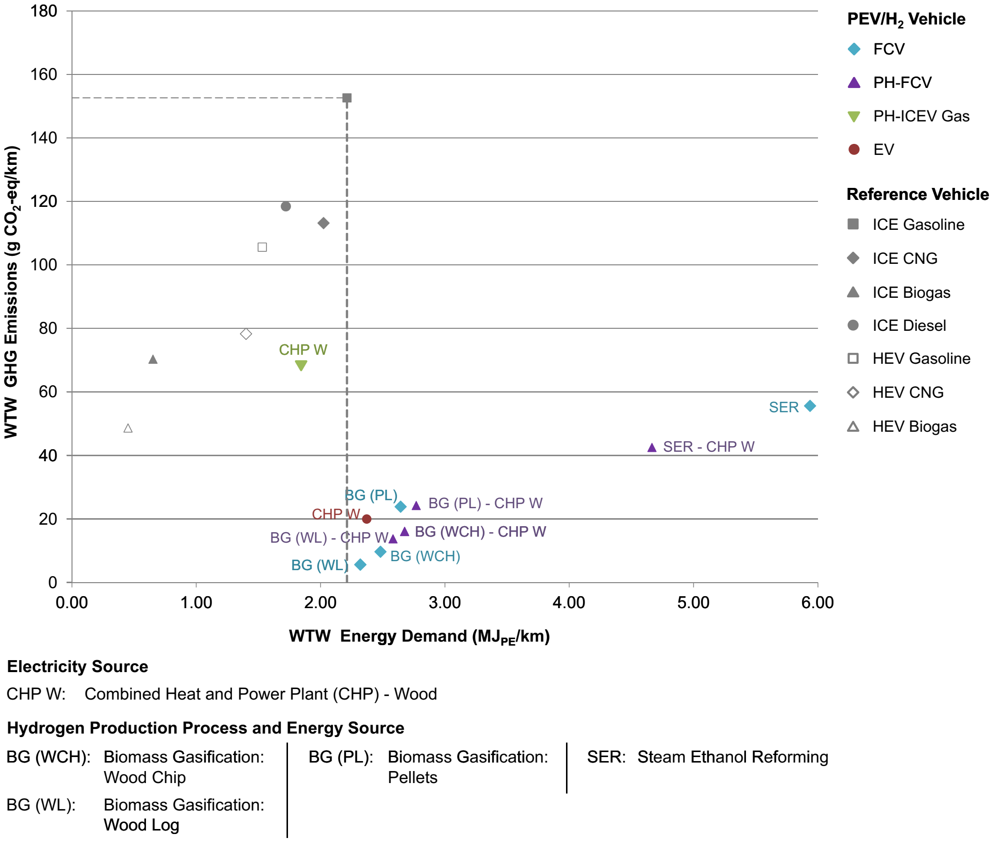

Fig. 10. WTW energy demand and GHG emissions via direct biomass (wood) energy conversion pathways for drivetrains based on reference vehicle characteristics.

respectively. Direct natural gas conversion pathways for hydrogen production include partial oxidation and steam methane reforming.

Amongst natural gas-based pathways, the largest reduction in WTW energy demand and GHG emissions is observed for the HEV_{CNG}. Steam methane reforming for fuel cell vehicles and PEV electrification via natural gas CCP also yield remarkable WTW energy demand and GHG emission reductions compared to the $ICEV_{Gas}$. Partial oxidation for hydrogen production and electricity generation via a natural gas CHP plant yield somewhat smaller, but nonetheless notable, WTW energy demand and emission reductions.

Overall, however, the HEV_{Bio} demonstrates the lowest WTW energy demand and GHG emissions.

The CHP plant demonstrates higher primary energy demand and GHG emissions than the CCP. However, CHP results vary according to the share of the burden allocated to heat production versus electricity production, as described in Section 4.2.1. An exergy-based allocation method is applied in Fig. 8a which places the majority of the burden on electricity (76%). At the opposite extreme, the majority of the burden can be allocated to heat (55%). Fig. 9 shows how drivetrain performance varies depending on the burden allocation method. The allocation method has a significant impact on drivetrain performance, particularly in the case of lower efficiency production pathways such as low temperature electrolysis.

6.2.2.3. Biomass. Two direct biomass conversion pathways for hydrogen production are presented in Fig. 10: biomass gasification and steam bioethanol reforming. The primary energy source is wood. Electricity is generated via a wood CHP plant.

WTW GHG emissions are reduced by over 50% for all biomass pathways presented. However, WTW energy demand varies significantly. Of the non-reference vehicles, only the PH-ICEV yields a lower energy demand than the $ICEV_{Gas}$, while steam ethanol reforming results in an energy demand more than twice that of the $ICEV_{Gas}$.

Overall, the most emission-competitive wood biomass pathways are given, in close range, by fuel cell drivetrains using biomass gasification for hydrogen production (via wood chips, wood logs, or pellets) and PEVs using wood CHP plants.

6.2.2.4. Solar. Solar energy pathways are presented in Fig. 11. Electricity is generated via a photovoltaic (PV) plant. Direct solar energy conversion pathways for hydrogen production include photobiological splitting and solar thermal dissociation.

As in the case of biomass, all solar energy pathways result in GHG emission reductions of over 50% compared to the $ICEV_{Gas}$, but the WTW energy demand varies significantly depending on the process, particularly amongst photobiological splitting processes.

Unlike in the case of biomass, the EV outperforms solar energy-based fuel cell drivetrains, particularly with respect to WTW energy demand. Hence, the EV using PV electricity appears to be the most promising solar energy-based pathway.

Amongst direct solar hydrogen production processes, direct photobiological splitting using hydrogenase results in the lowest WTW energy demand and GHG emissions. Solar thermal dissociation yields low WTW emissions as well, but relatively high energy demand.

7. Conclusion

This study presents a comprehensive comparison of operational well-to-wheel energy demand and GHG emissions for different passenger car drivetrain technologies and energy carrier production pathways. All energy carrier WTW results pertain to end-use in

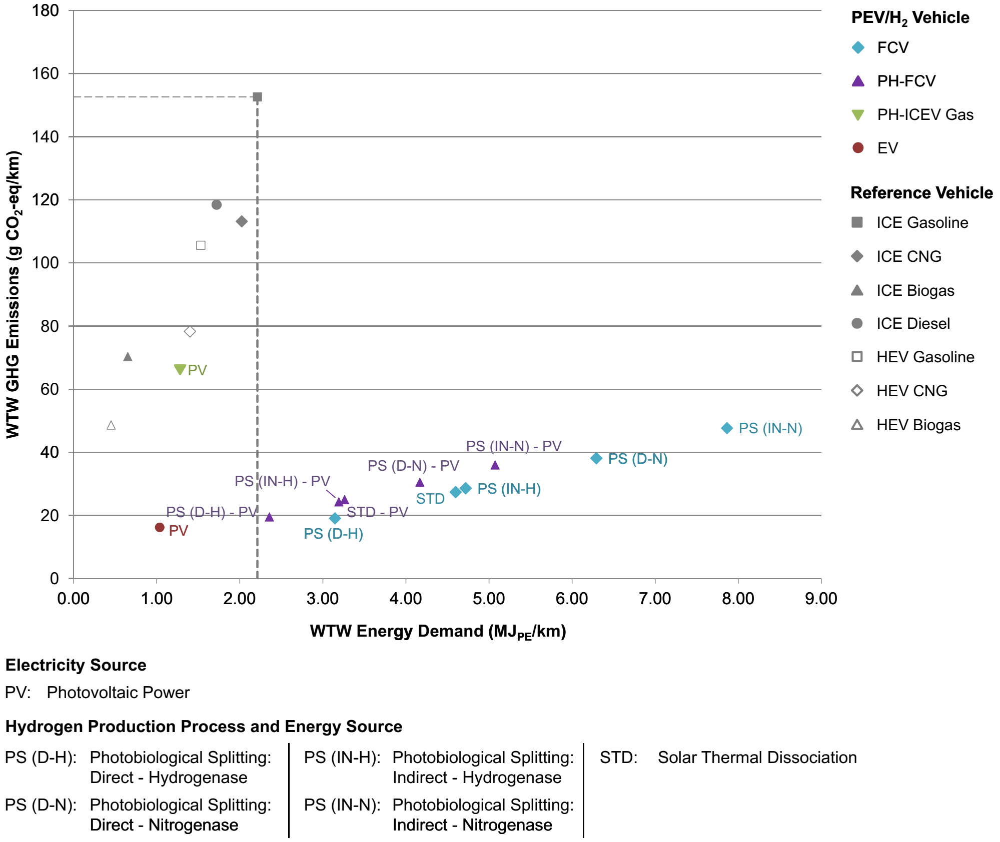

Fig. 11. WTW energy demand and GHG emissions via direct solar energy conversion pathways for drivetrains based on reference vehicle characteristics.

Switzerland. Several pathways have been identified which demonstrate WTW energy demand and GHG emission reductions compared to the conventional gasoline ICE reference vehicle.

7.1. PEV and fuel cell drivetrain performance for direct and indirect electricity conversion pathways

Overall, a strong case is presented for the direct electrification of PEVs. Full battery-electric vehicles demonstrate some of the lowest WTW energy demand and GHG emissions amongst all drivetrains due to relatively high energy conversion chain efficiencies. However, WTW performance strongly depends on the electricity generation method or mix used. Renewable energy-based electricity generation results in low WTW GHG emissions, while fossil fuel-based electricity can lend itself to higher emissions than the gasoline ICE. In this study, the lowest WTW energy demand and GHG emissions were achieved using electricity from waste incineration, biogas CHP, hydropower, wind power, and photovoltaic power.

Plug-in hybrid ICE-electric vehicles yielded lower WTW energy demand and GHG emissions than the $ICEV_{Gas}$ for all electricity sources evaluated. However, this result is a function of the electric share (and, of course, the electricity mix). A critical electricity mix can be identified which divides optimal drivetrain performance between the EV, PH-ICEV, and ICEV.

Fuel cell drivetrains using electrolysis for hydrogen production are more sensitive to variations in the electricity mix compared to PEVs due to a lower overall energy conversion efficiency chain. However, direct chemical conversion processes for hydrogen production offer efficiency gains which can reduce or eliminate the gap between EV and FCV operational WTW performance, as follows.

7.2. PEV and fuel cell drivetrain performance by natural resource category

A comparison of direct chemical conversion pathways for energy carrier production revealed optimal alternative drivetrain and energy carrier production pathways for each natural resource category. Coal energy does not provide viable alternative drivetrain pathways; however, biomass, natural gas, and solar energy-based pathways do. With respect to biomass, both fuel cell and PEV drivetrains yielded remarkably lower WTW GHG emissions than the $ICEV_{Gas}$ where biomass gasification was used for hydrogen production and electricity was generated via a wood CHP plant. WTW energy demand was comparable to the $ICEV_{Gas}$ for these configurations. Natural gas pathways revealed that both WTW GHG emissions and WTW energy demand were significantly reduced using steam methane reforming-based fuel cell drivetrains and natural gas CCP-based PEV drivetrains. Partial oxidation and direct electrification by natural gas CHP plants also resulted in reduced WTW energy demand and GHG emissions.

EV electrification using photovoltaic power resulted in the lowest solar energy pathway WTW energy demand and GHG emissions. Fuel cell drivetrains were able to achieve GHG emissions in a similar range (due to the higher efficiency of some photobiological splitting processes compared to PV power generation), but the corresponding WTW energy demand exceeded that of the $ICEV_{Gas}$. Direct photobiological splitting using hydrogenase performed well compared to other direct solar energy conversion pathways for H_2 production.

7.3. ICE drivetrain technologies and alternative fuels

Pluggable electric and fuel cell drivetrains were not the only vehicles to demonstrate significant potential to improve upon the WTW energy demand and GHG emissions of the $ICEV_{Gas}$. ICEV and HEV drivetrains using alternative fuels, particularly biogas and CNG, also resulted in remarkable reductions. In the case of biogas, for example, reductions were over 50% compared to the $ICEV_{Gas}$. The HEV_{CNG} also resulted in the lowest WTW energy demand and GHG emissions of all natural gas-based pathways evaluated. Hence, alternative fuel sources, and not only alternative drivetrain technologies, play a key role in improving WTW energy demand and GHG emissions. This is a positive outcome in light of the implementation and infrastructure challenges associated with alternative drivetrain technologies.

7.4. Results in context

The results of this study serve as valuable inputs not only for policy decision-makers and technology experts in Switzerland, but also internationally. Switzerland differs from other European and non-European countries in that it enjoys a low-emission electricity mix due to the predominance of hydro and nuclear power. However, regions using alternative mixes can derive relative results and benefit from key observations from this study given technical similarities in drivetrain technologies and energy carrier production processes worldwide.

Several observations in this investigation agree with findings from earlier studies performed in the context of both developing and developed countries. For instance, in the case of fossil fuel-based electrolysis for FCV hydrogen production in China, coal also yields higher WTW GHG emissions than a gasoline ICE, while steam methane reforming yields significant emission reductions [3]. The sensitivity of PEV energy demand and emissions to the electricity generation method is also observed in Refs. [6,9,10], and the sensitivity of FCV performance to hydrogen production processes is observed in Ref. [8]. Renewable energy-based pathways, including solar and wind energy-based electrolysis, are suggested as potential pathways to reduce non-renewable resource consumption in Ref. [11] as well.

Results from prior studies, together with the insights offered by this investigation into a wider range of energy carrier production processes and natural resource categorizations, provide a useful relative analysis with global applications.

In order to build a more comprehensive study, further investigations should additionally consider the WTW energy demand and GHG emissions for vehicle production, maintenance, and disposal, as well as costs.

Acknowledgments

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