A sustainable market niche for hydrogen in the transport sector ?

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Introduction

Context

- Transportation is responsible for 24% of direct CO_2 emissions from fuel combustion in the European Union. Road transport accounts for 18% of these total emissions, and heavy-duty transport for 6% (EU Commission).
- In the road transport sector, a 100% electric and net zero carbon scenario is possible, but involve additional challenges and undesirable side effects (IEA, 2021)
- BloombergNEF (2020) notes the need for a clean molecule for the full decarbonization of the transport sector and emphasizes hydrogen as a good candidate for this role.
- This paper contributes to the economics literature on the role of battery-electric vehicles (BEVs) and fuel cell-electric vehicles (FCEVs) in mobility.

The critical parameters

- Competition between battery-electric vehicles (BEVs) and fuel cell-electric vehicles (FCEVs) in heavy-duty mobility

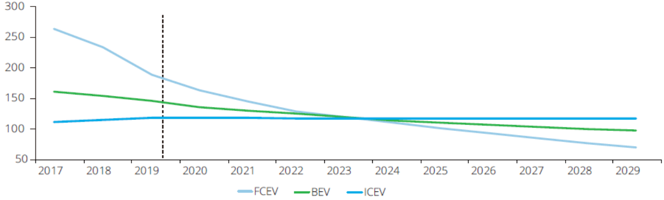

Figure 1: Bus Total Cost of Ownership (TCO) : Outlook in Europe (unit: USD/ per 100km) for FCEVs, BEVs and ICEVs (source: Ballard, 2020)

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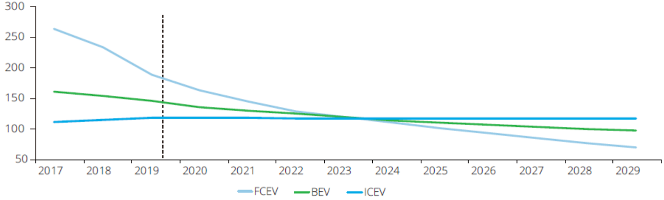


Figure 1: Bus Total Cost of Ownership (TCO) : Outlook in Europe (unit: USD/ per 100km) for FCEVs, BEVs and ICEVs (source: Ballard, 2020)

- The critical factors:
  - **Long term TCO** of low-carbon technologies
  - **Learning rate** of technologies
  - **Potential niche market size** for hydrogen
  - **Additional cost for using BEVs** in the niche market
  - **Exogenous transition duration** in the niche market

Literature Review

Regarding the cost-reduction of low-carbon technologies, the economic literature (Grubb and Koehler, 2002) makes the distinction between

- **Technology R&D:** new fuel cells prototype, solid-state batteries, ...
- **Endogenous learning-by-doing** (Arrow, 1964): economies of scale due to the deployment of hydrogen mobility in the European Market
- **Exogenous and autonomous technical change:** Cost reductions thanks to other economic and geographic sectors

Existing economic models on green technologies:

- Competition between a carbon-based technology and a low-carbon technology: Grimaud and Rouge (2008), Acemoglu (2012), Creti et. al (2017)
- Competition between two low-carbon technologies: Bramoulle and Olson (2002), Andreassen and Rosendahl (2020)

Research questions addressed in this paper

- **Competition between low-carbon technologies**: Is it better to focus on one technology to maximize learning-by-doing ? Or is it better to develop two technologies on their respective markets ?
- **Optimal deployment of low-carbon technologies**: What are the optimal launching dates for the energy transition in the heavy-duty transport sector? What are the optimal deployment trajectories of low-carbon technologies?
- **Hydrogen strategy for government and business:** Will hydrogen have a sustainable niche in the transport sector? What are the conditions for the emergence of a hydrogen segment in heavy-duty transport ?

From one to two green technologies: an economic model

From one to two Technologies: The Economic Model

Extension of Creti et al. (2017): Each year t, N vehicles are built, among which x_t use a low-carbon technology 1 (battery), y_t use a low-carbon technology 2 (fuel cell), and $N - x_t - y_t$ use a carbon-based technology (diesel). The marginal cash cost of diesel vehicles is fixed (c_0) but their costs increase with the price of CO_2, $p_t^{CO2} = p_0 e^{rt}$, with r the discount rate. The social planner minimises the total discounted cost:

$$\Gamma = \int_0^{+\infty} e^{-rt} \Big[\underbrace{(p_t^{CO2} + c_0)(N - x_t - y_t)}_{\text{Diesel vehicle costs}} + \underbrace{C_1(X_t, x_t)}_{\text{BEV costs}} + \underbrace{C_2(Y_t, y_t)}_{\text{FCEV costs}} \Big] dt$$

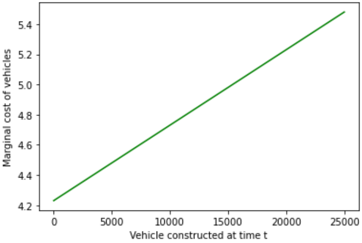
Under the following constraints:

$$\dot{X}_t = x_t \qquad \dot{Y}_t = y_t$$

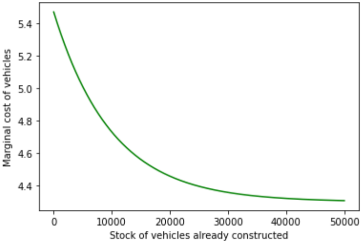
$$X_0 = 0 \qquad Y_0 = 0$$

$$x_t \geq 0 \qquad y_t \geq 0 \qquad x_t + y_t \leq N$$

Cost function of green technologies



Convexity effect ($C_{xx} \geq 0$):
The more vehicles built at date t, the higher the marginal cost (financing constraints, infrastructure, workforce, ...)



Learning effect ($C_{Xx} \leq 0$):
The larger the stock of vehicles built, the lower the marginal cost (economies of scale, industrialization)

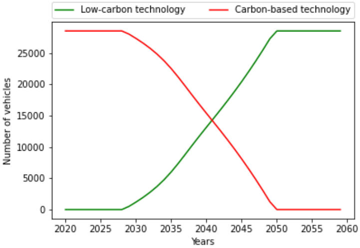
Different phases of optimal transition

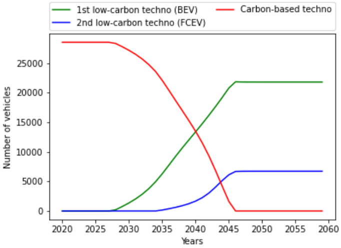
Proposition 1 *Denoting* (x_t^*, X_t^*) *and* (y_t^*, Y_t^*) *the optimal productions and stocks along the optimal deployment trajectory, there are two dates* T_{in} *and* T_{out} *such that three deployment phases can be identified:*

Pre-transition phase : for $0 \leq t \leq T_{in}$ we have $x_t^* = 0$ and $y_t^* = 0$

Transition phase : for $T_{in} < t < T_{out}$ we have $0 < x_t^* + y_t^* < N$

Post-transition phase : for $t \geq T_{out}$ we have $x_t^* + y_t^* = N$.


One low-carbon technology


Two low-carbon technologies

Transition phase $(0 < x_t^* + y_t^* < N)$

During the transition phase (Z_t and z_t the stock of knowledge and the instantaneous production of a green technology)

- Between T_{in} and T_{out}, if $z_t > 0$, it satisfies the following equation

$$\underbrace{[C_{i,z}(Z_t^*, z_t^*) - c_0]}_{\text{Static abatement cost}} = p_t^{CO2} - \underbrace{\int_t^{+\infty} e^{-r(\tau - t)} C_{i,Z}(Z_\tau^*, z_\tau^*) d\tau}_{\text{Learning Benefit}(<0)}$$

  and given that the SCC p_t^{CO2} grows at the discount rate, the trajectory $z_{t-T_{in}}$ does not depend on p_t^{CO2}, which extends a result proved in Creti et al. (2017), but the launching dates do.

- The optimal transition trajectory respects the following second order differential equation:

$$C_{i,xx}\ddot{Z}_t + C_{i,zZ}\dot{Z}_t - rC_{i,z} - C_{i,Z} + rc_0 = 0 \text{ for } t > T_{in}$$

Post-transition phase ($x_t^* + y_t^* = N$)

During the post-transition phase

- If both technologies are used the first order condition is:

$$C_{1,x}(X_t^*, x_t^*) - C_{2,y}(Y_t^*, y_t^*) = \int_t^{+\infty} e^{-r(\tau - t)}[C_{1,X}(X_\tau^*, x_\tau^*) - C_{2,Y}(Y_\tau^*, y_\tau^*)]d\tau$$

with $y_\tau^* = N - x_\tau^*$ and $Y_\tau^* = Y_{T_{out}} + (\tau - T_{out})N - (X_\tau^* - X_{T_{out}})$

- **The market share of the two technologies evolves**. One green technology may be progressively replaced by the other, and on the long-run either the two technologies coexist **(convexity effect)** or one of the two technologies prevails **(learning effect)**.

Solving a specific case: No cost convexity ($C_{xx} = 0$)

Proposition 2

In absence of convexity in the cost functions, the optimal strategy is to replace all dirty vehicles instantaneously, $T_{in} = T_{out}$*, with only one green technology, the other is unused.*

When comparing several green technologies with cost functions of the exponential form, the best technology is the one with the earlier launching date or, equivalently, the one with the lowest accumulated emissions.

A deployment perspective for BEBs vs FCEBs

Modeling the imperfect substitution of technologies

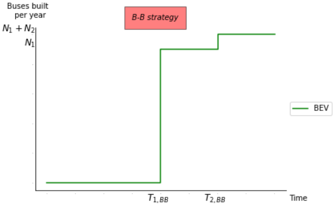
In practice, one technology can be preferred to another not only for its cost, but also for its use: **imperfect substitution**.

- **Segmented Market:** The total number of buses N is the sum of N_1 standard battery users and N_2 niche users, with $N_1 > N_2$.
- **Main Market** N_1: let C_{BEV} and C_{FCEV} denote the cost of operating one battery and one fuel cell bus in the N_1 segment respectively. By assumption $C_{BEV} < C_{FCEV}$ when comparing identical trajectories.
- **Niche Market** N_2: for the N_2 users, the marginal cost of FCEV is C_{FCEV}, the cost of BEV is $C_{BEV} + d$ with d a positive cost penalty for BEV on the niche market. For some values of d, it may be beneficial to launch FCEV on the niche market.

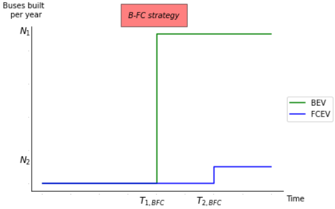
Candidate strategies for optimal deployment

If $d \neq 0$, there are only two candidate strategies for the optimal deployment of a low-carbon fleet:

B-B strategy: Battery is used over the two segments. It is used on N_1 because of its cost advantage and on N_2 in spite of its additional cost d per vehicle.



B-FC strategy: both technologies are used: battery on N_1 and fuel cell on N_2.



Calibrated key parameters

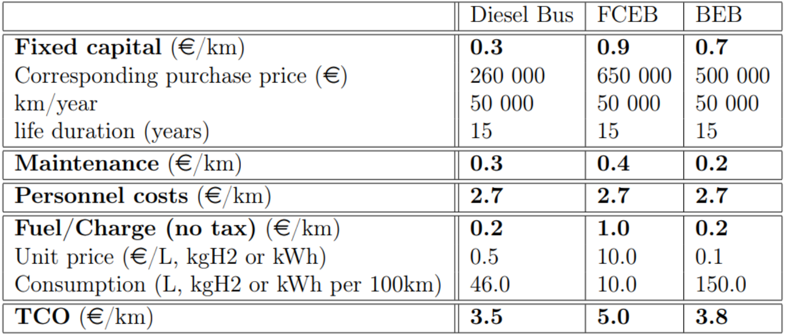
Classic learning curve: $C_i(Z_t, z_t) = \overline{c_i} e^{-\lambda_i Z_t} z_t$, in which $\overline{c_i}$ is the short-term marginal cost, λ_i the learning rate, Z_t the stock of buses built during t years, z_t the bus built at date t.

Adjusted learning curve: $C_i(Z_t, z_t) = [\underline{c_i} + (\overline{c_i} - \underline{c_i}) e^{-\lambda_i Z_t}] z_t$, in which $\underline{c_i}$ is the long-term marginal cost.

	BEV	FCEV
Long term marginal cost $\underline{c_i}$ (/km)	3.4	3.4
Parity year with diesel bus	2025	2035
Learning rate λ_i	0.00001	0.0001
Niche market relative size θ (N_2/N) (%)	10 %	
Additional cost for BEBs on the niche market d (/km)	0.3	
Exogenous transition duration D_i (years)	5	10

Table 1: Estimated values for the key parameters

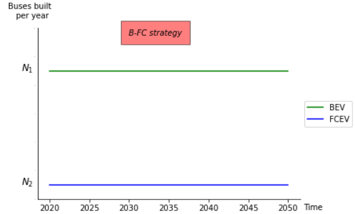
Short-term marginal cost $\overline{c_i}$

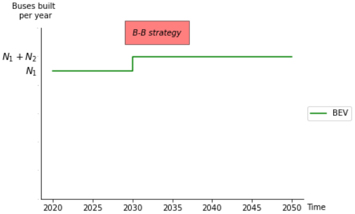


	Diesel Bus	FCEB	BEB
Fixed capital (€/km)	**0.3**	**0.9**	**0.7**
Corresponding purchase price (€)	260 000	650 000	500 000
km/year	50 000	50 000	50 000
life duration (years)	15	15	15
Maintenance (€/km)	**0.3**	**0.4**	**0.2**
Personnel costs (€/km)	**2.7**	**2.7**	**2.7**
Fuel/Charge (no tax) (€/km)	**0.2**	**1.0**	**0.2**
Unit price (€/L, kgH2 or kWh)	0.5	10.0	0.1
Consumption (L, kgH2 or kWh per 100km)	46.0	10.0	150.0
TCO (€/km)	**3.5**	**5.0**	**3.8**

Figure 2: TCO analysis of Diesel bus, FCEB, BEB in 2021

Deployment strategies: with or without transition duration





Deployment strategies: with or without transition duration

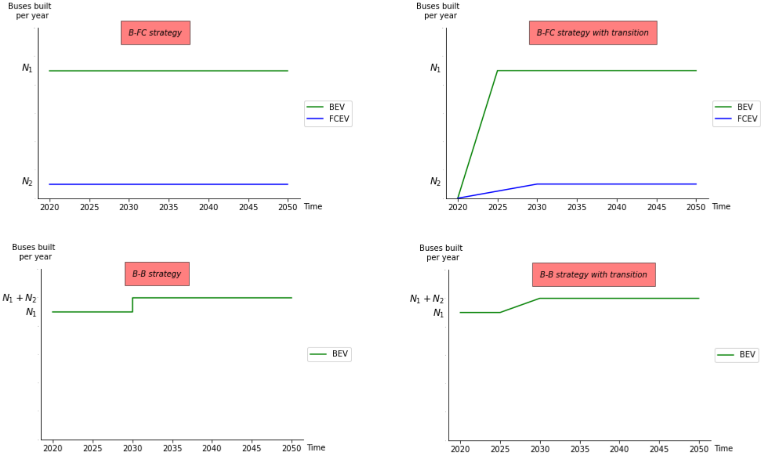
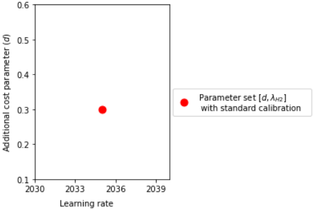
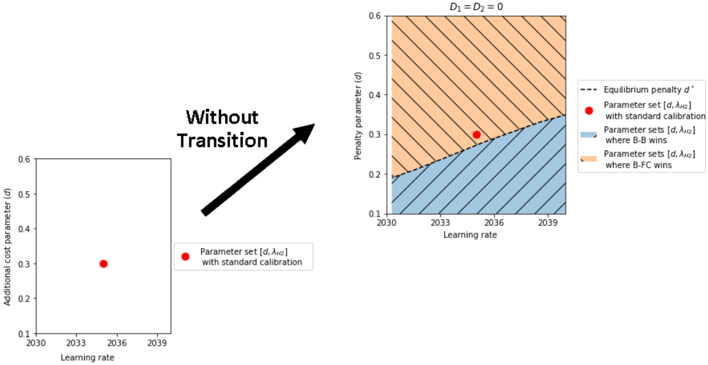


Figure 3: Fleet deployment strategies without or with transition duration (5 years for BEBs, 10 years for FCEBs)

Sensitivity analysis on the learning rate and the additional cost for BEBs on the niche market



Sensitivity analysis on the learning rate and the additional cost for BEBs on the niche market



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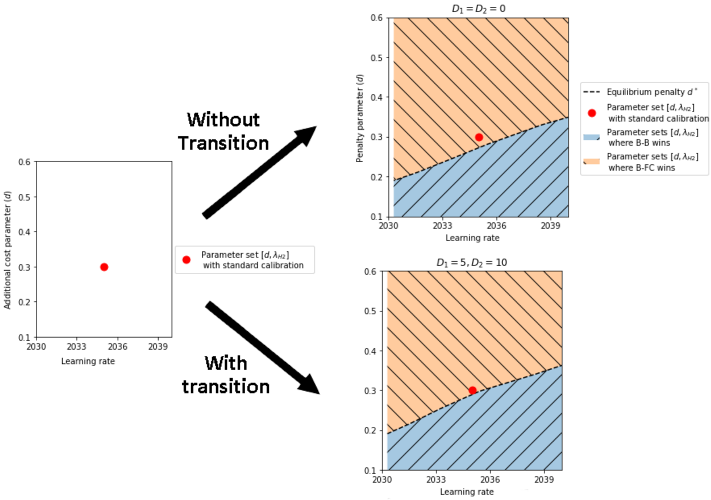

Threshold penalty d^* and sensitivity analysis

Figure 4: Evolution of d*, penalty ensuring indifference between both strategies, as a function of the learning rate of the FCEB technology

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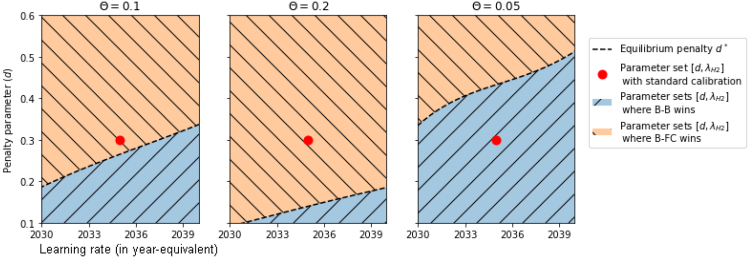


Figure 4: Evolution of d*, penalty ensuring indifference between both strategies, as a function of the learning rate of the FCEB technology: sensitivity analysis on the niche market size $\theta = 10\%, 20\%, 5\%$

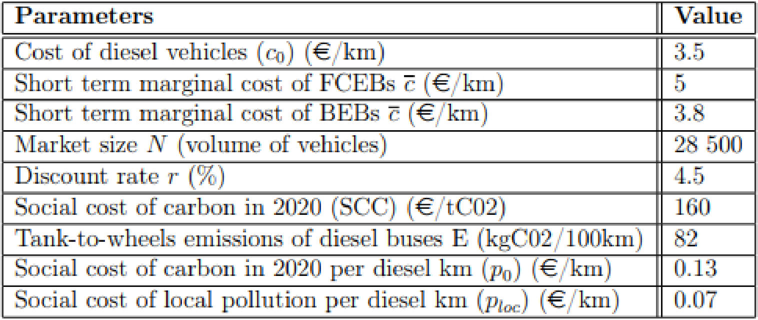
Conclusion and extensions

- This paper clarifies the impacts of learning-by-doing, transition duration and imperfect substitution on the optimal transition path when several green competing technologies are available to decarbonize a given mobility segment.
- This analysis uses dynamic abatement costs to assess energy transition options in the transport sector.
- Applied to the case of FCEBs and BEBs to decarbonize the European park of diesel buses, hydrogen mobility has a sustainable niche with our baseline parameter values.

Extensions:

- Other competing low-carbon technologies (biofuels, e-fuels)
- Demand for mobility: choice of motorization for consumers
- Impact of environmental externalities on the competition between low carbon technologies

Back-up: Calibrated basic parameters



Parameters	**Value**
Cost of diesel vehicles (c_0) (€/km)	3.5
Short term marginal cost of FCEBs $\bar{c}$ (€/km)	5
Short term marginal cost of BEBs $\bar{c}$ (€/km)	3.8
Market size N (volume of vehicles)	28 500
Discount rate r (%)	4.5
Social cost of carbon in 2020 (SCC) (€/tC02)	160
Tank-to-wheels emissions of diesel buses E (kgC02/100km)	82
Social cost of carbon in 2020 per diesel km (p_0) (€/km)	0.13
Social cost of local pollution per diesel km (p_{loc}) (€/km)	0.07

Figure 5: Estimated basic parameters of battery and hydrogen technology in the model