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 (FCEBs) in mobility.

Introduction

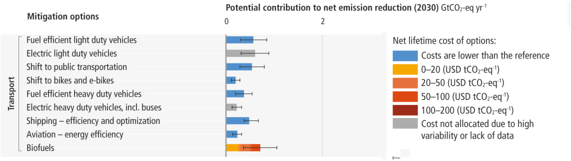


Figure 1: Overview of mitigation options in transport and their estimated ranges of costs and potentials in 2030, IPCC 3rd WG 2022

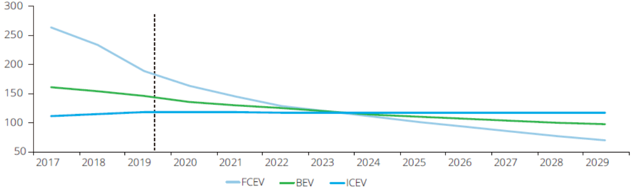


Figure 2: Bus TCO outlook in Europe (unit: USD/ per 100km)

Economic Literature

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), 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 cost of diesel vehicles is fixed (c_0) but their cost increases 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:

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

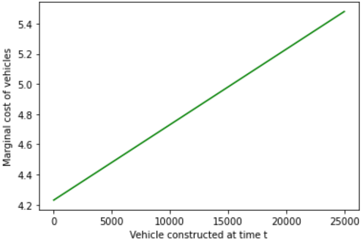
Under the following constraints:

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

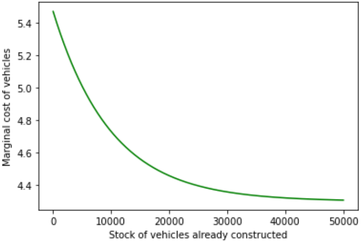
$$X_0 = 0 \qquad Y_0 = 0$$

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

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

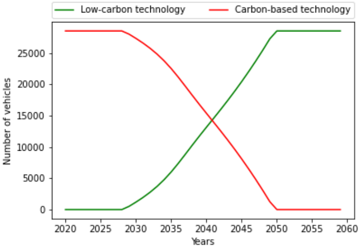
Proposition 1 *Denoting* (x_t^*, X_t^*) *and* (y_t^*, Y_t^*) *the optimal productions and stocks along the optimal deployment trajectory, there are two dates* T_{in} *and* T_{out} *such that three deployment phases can be identified:*

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

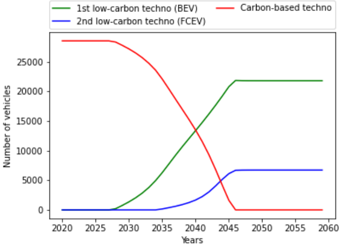
Transition phase : for $T_{in} < t < T_{out}$ we have $0 < x_t^* + y_t^* < N$

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 ($C_{xx} = 0$)

Corresponding non-convex cost function: $\overline{c_i}$ (current marginal cost), $\underline{c_i}$ (marginal cost after maximal learning), λ_i (learning rate)

$$C_i(Z_t, z_t) = [\underline{c_i} + (\overline{c_i} - \underline{c_i})e^{-\lambda_i Z_t}]z_t$$

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. The technology with the earlier launch date should be selected.*

The discounted cost of the post-transition phase for technology i is:

$$K_i = \int_0^{+\infty} e^{-rt} C_i(tN, N)dt = \underline{c_i}\frac{N}{r} + (\overline{c_i} - \underline{c_i})\frac{N}{r + \lambda_i N}$$

The total discounted cost for technology i is :

$$\Gamma_i^* = p_0^{CO2} N T_i^* + \frac{N(c_0 + p_0^{CO2})}{r}, \text{ with } T_i^* = \frac{1}{r} ln(\frac{rK_i}{p_0 N})$$

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.
- **Corresponding non-convex cost function:**

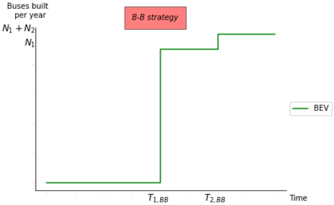
$$C_{BEV}(X_t) = [\underline{c_{BEV}} + (\overline{c_{BEV}} - \underline{c_{BEV}})e^{-\lambda_{BEV} X_t}]$$

$$C_{FCEV}(Y_t) = [\underline{c_{FCEV}} + (\overline{c_{FCEV}} - \underline{c_{FCEV}})e^{-\lambda_{FCEV} Y_t}]$$

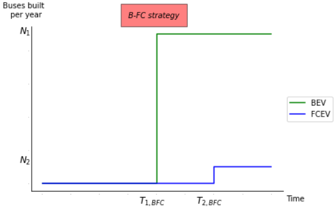
Optimal deployment strategies

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

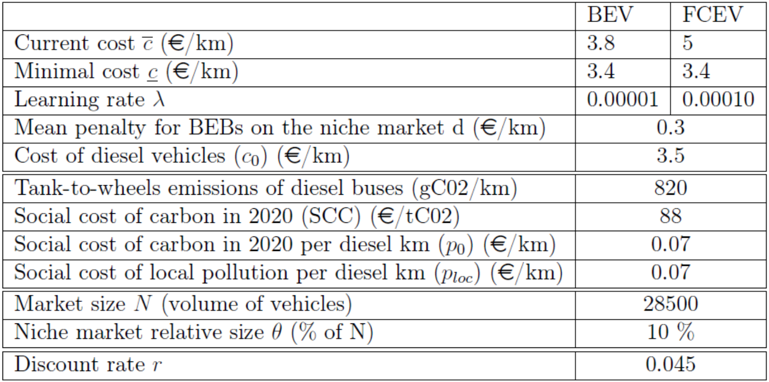
B-B strategy: Battery is used over the two segments. It is used on N_1 because of its cost advantage and on N_2 in spite of its additional cost d per vehicle.



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



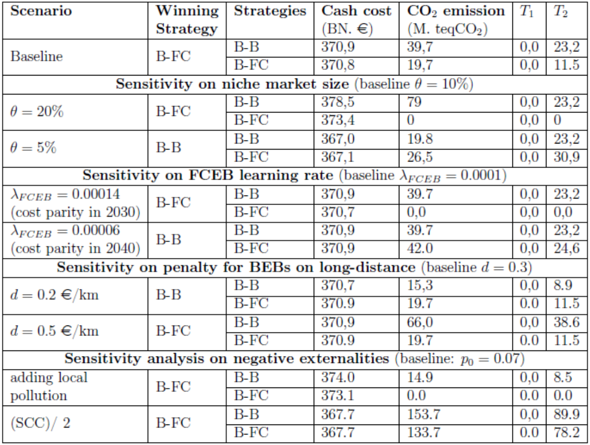
Calibrated parameters



	BEV	FCEV
Current cost $\overline{c}$ (€/km)	3.8	5
Minimal cost $\underline{c}$ (€/km)	3.4	3.4
Learning rate λ	0.00001	0.00010
Mean penalty for BEBs on the niche market d (€/km)	0.3	
Cost of diesel vehicles (c_0) (€/km)	3.5	
Tank-to-wheels emissions of diesel buses (gC02/km)	820	
Social cost of carbon in 2020 (SCC) (€/tC02)	88	
Social cost of carbon in 2020 per diesel km (p_0) (€/km)	0.07	
Social cost of local pollution per diesel km (p_{loc}) (€/km)	0.07	
Market size N (volume of vehicles)	28500	
Niche market relative size θ (% of N)	10 %	
Discount rate r	0.045	

Figure 3: Estimated parameters of battery and hydrogen technology in the model (TCO analysis in figure (8))

Results and sensitivity analysis



Scenario	**Winning Strategy**	**Strategies**	**Cash cost** (BN. €)	**CO$_2$ emission** (M. teqCO$_2$)	T_1	T_2
Baseline	B-FC	B-B	370,9	39,7	0,0	23,2
		B-FC	370,8	19,7	0,0	11.5
Sensitivity on niche market size (baseline $\theta = 10\%$)						
$\theta = 20\%$	B-FC	B-B	378,5	79	0,0	23,2
		B-FC	373,4	0	0,0	0
$\theta = 5\%$	B-B	B-B	367,0	19.8	0,0	23,2
		B-FC	367,1	26,5	0,0	30,9
Sensitivity on FCEB learning rate (baseline $\lambda_{FCEB} = 0.0001$)						
$\lambda_{FCEB} = 0.00014$ (cost parity in 2030)	B-FC	B-B	370,9	39.7	0,0	23,2
		B-FC	370,7	0,0	0,0	0,0
$\lambda_{FCEB} = 0.00006$ (cost parity in 2040)	B-B	B-B	370,9	39.7	0,0	23,2
		B-FC	370,9	42.0	0,0	24,6
Sensitivity on penalty for BEBs on long-distance (baseline $d = 0.3$)						
$d = 0.2$ €/km	B-B	B-B	370,7	15,3	0,0	8.9
		B-FC	370.9	19.7	0.0	11.5
$d = 0.5$ €/km	B-FC	B-B	370,9	66,0	0,0	38.6
		B-FC	370.9	19.7	0.0	11.5
Sensitivity analysis on negative externalities (baseline: $p_0 = 0.07$)						
adding local pollution	B-FC	B-B	374.0	14.9	0,0	8.5
		B-FC	373.1	0.0	0.0	0.0
(SCC)/ 2	B-FC	B-B	367.7	153.7	0,0	89.9
		B-FC	367.7	133.7	0.0	78.2

Figure 4: Key indicators on B-FC and B-B strategies for the baseline scenario, with sensitivity analysis on model parameters

Equilibrium penalty d^* and sensitivity analysis

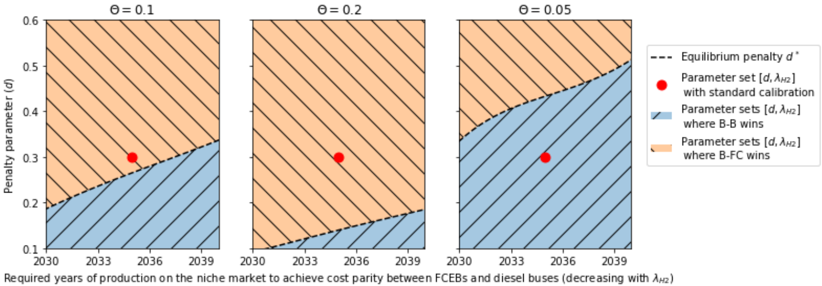


Figure 5: Evolution of d*, penalty ensuring indifference between both strategies, as a function of the learning rate of the FCEB technology: sensitivity analysis on the niche market size $\theta = 10\%, 20\%, 5\%$

Equilibrium penalty with exogenous transition duration

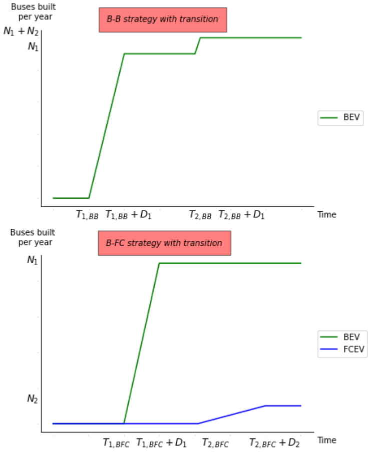


Figure 6: Fleet deployment strategies with exogenous transition duration, B-B (top) and B-FC (bottom)

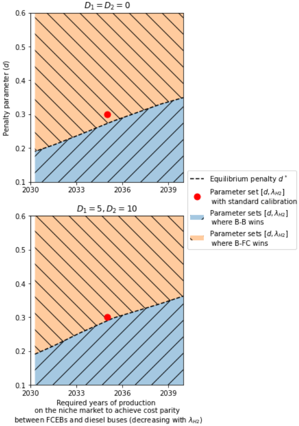


Figure 7: Sensitivity analysis on d^*: $D_1 = 0, D_2 = 0$ and $D_1 = 5, D_2 = 10$

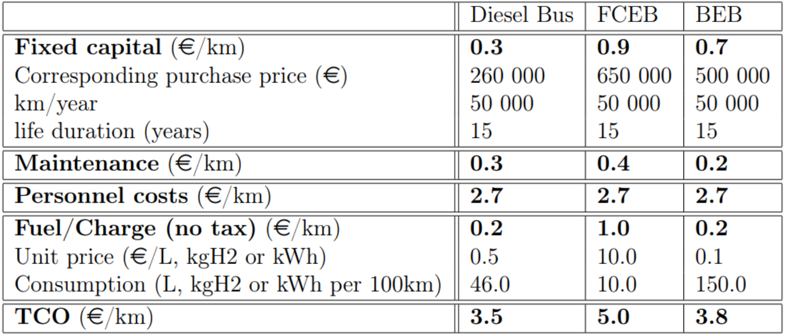
Conclusion and extensions

- This paper clarifies the impacts of learning-by-doing, convexity 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

Annex: Cost calibration



	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 8: TCO analysis of Diesel bus, FCEB, BEB in 2021

- Cost parity of BEB with diesel buses by 2025-2027
- Cost parity of FCEB with diesel buses by 2035