

Table of Contents

1	Introduction	1
1.1	Introduction	1
1.2	Context	2
1.3	Justification	7
1.4	Objectives	8
1.5	General outline	9
	References	12
2	Literature review	13
2.1	Introduction	13
2.2	H ₂ as an energy carrier	14
2.3	Fuel cell technology	16
2.4	Passenger car FCV	19
	2.4.1 Fuel cell range-extender architecture	21
2.5	Heavy-duty FCV	23
2.6	Fuel cell degradation	25
2.7	Summary and conclusions	29
	References	31
3	Methodology	37
3.1	Introduction	38
3.2	Methodology Outline	38
3.3	Fuel cell stack model	40

3.3.1	Numerical description	40
3.3.2	Validation	41
3.4	Fuel cell system model	44
3.4.1	Balance of plant outline.....	44
3.4.2	Balance of plant limitations	46
3.5	Fuel cell electric vehicle platform	47
3.5.1	Passenger car	48
3.5.2	Heavy-duty vehicle	49
3.6	Energy management strategy	50
3.7	Fuel cell degradation model.....	56
3.7.1	Degradation model outline	60
3.7.2	1 st layer: reference degradation rates	60
3.7.3	2 nd layer: electrochemical phenomena.....	62
3.7.3.1	Low-power/idle condition	62
3.7.3.2	Load-change condition.....	64
3.7.3.3	High-power condition.....	65
3.7.3.4	Medium-power/natural degradation	66
3.7.4	3 rd layer: physical conditions	67
3.7.4.1	Effect of temperature on degradation.....	68
3.7.4.2	Effect of relative humidity on degradation...	69
3.7.5	Degradation model integration	70
3.7.5.1	Integration along the PEMFC polarization curve.....	70
3.7.5.2	Integration with PEMFC models	72
3.7.6	Validation	73
3.8	Life cycle assessment.....	75
3.8.1	Boundaries and environmental flows	75
3.8.2	Functional unit	77
3.8.3	Impact categories	77
3.8.4	Life cycle inventory	78

3.8.4.1	Fuel production LCI	78
3.8.4.2	Vehicle manufacturing LCI.....	79
3.8.4.3	Operation cycle LCI	81
3.9	Driving cycle simulation procedure	81
3.10	Summary and conclusions	85
	References	86
4	Fuel Cell Electric Vehicle Powerplant Optimization	91
4.1	Introduction	92
4.2	Fuel cell system energy balance optimization.....	93
4.2.1	Optimization space.....	93
4.2.2	Optimum Energy Balance Identification	97
4.2.2.1	Passenger car	97
4.2.2.2	Heavy-duty vehicle.....	101
4.3	FCREx architecture for the passenger car application	104
4.3.1	Effect of powertrain components sizing on performance	105
4.3.2	Effect of energy management strategy dynamic and operational limits on performance and FC durability .	114
4.3.2.1	Effect of limiting $ di/dt $	114
4.3.2.2	Effect of limiting i_{min}	119
4.3.2.3	Simultaneous limitation of $ di/dt $ and i_{min} ..	124
4.3.3	Cross-effect of dynamics-limited energy management strategy sizing on performance and FC durability	130
4.3.3.1	Effect over the FCS behaviour.....	130
4.3.4	Effect on FCV performance	134
4.3.5	Effect on FC stack durability	136
4.4	Multi-FCS architecture for heavy-duty vehicle applications ..	139
4.4.1	Effect of dynamics-limited energy management strategy on performance and FC durability	140
4.4.2	Cross-effect of dynamics-limited energy management strategy and FCS sizing on performance and FC durability	146

4.5	Summary and conclusions	151
	References	156
5	Life cycle emissions optimization	157
5.1	Introduction	157
5.2	Cradle-to-grave emissions of FCREx vehicles	159
5.2.1	Impact of FCREx design on consumption and the manufacturing cycle	159
5.2.2	Cradle-to-grave and fuel production GHG-100 emissions	163
5.2.3	Cradle-to-grave and fuel production NO _x emissions ..	168
5.2.4	Blue and green H ₂ comparison	172
5.2.5	Potential of FCREx architecture to decrease cradle-to- grave emissions	174
5.3	Cradle-to-grave emissions of Multi-FCS HDV	176
5.3.1	GHG-100 cradle-to-grave emissions of heavy-duty FCV	177
5.3.2	NO _x cradle-to-grave emissions of heavy-duty FCV ...	185
5.4	Summary and conclusions	190
	References	192
6	General conclusions and future work	193
6.1	Introduction	193
6.2	Conclusions	193
6.2.1	Fuel Cell Electric Vehicle Powerplant Optimization ...	194
6.2.2	Life cycle emissions optimization conclusions	197
6.3	Future work	198
	References	202
	References	203