Integrating Transport Dynamics into the TIMES-Reunion Model: Exploring Energy Transition Pathways Toward Self-Sufficiency and Carbon Neutrality

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- PhD Thesis :
  Economic analysis of energy and food self-sufficiency on Reunion Island
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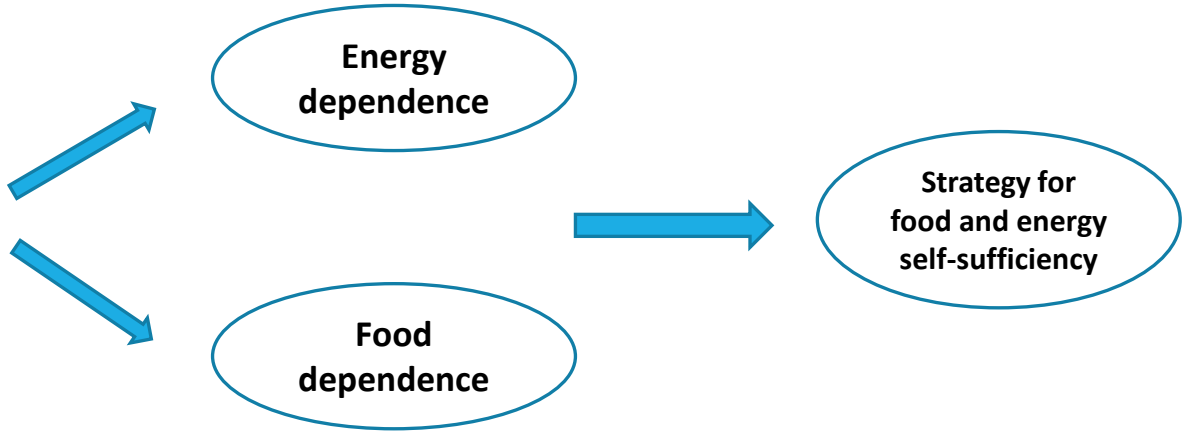
Insular Economy

Vulnerability :

- Geographic isolation
- Limited land surface



General Overview of the work

Context of Reunion Island :

- **2015 French Law on Energy Transition for Green Growth (LTECV)**
  - Energy autonomy for the French overseas territories by 2030
- **Food autonomy:** on the French political agenda since 2019

Land

Food

sugar cane
56% agricultural Land

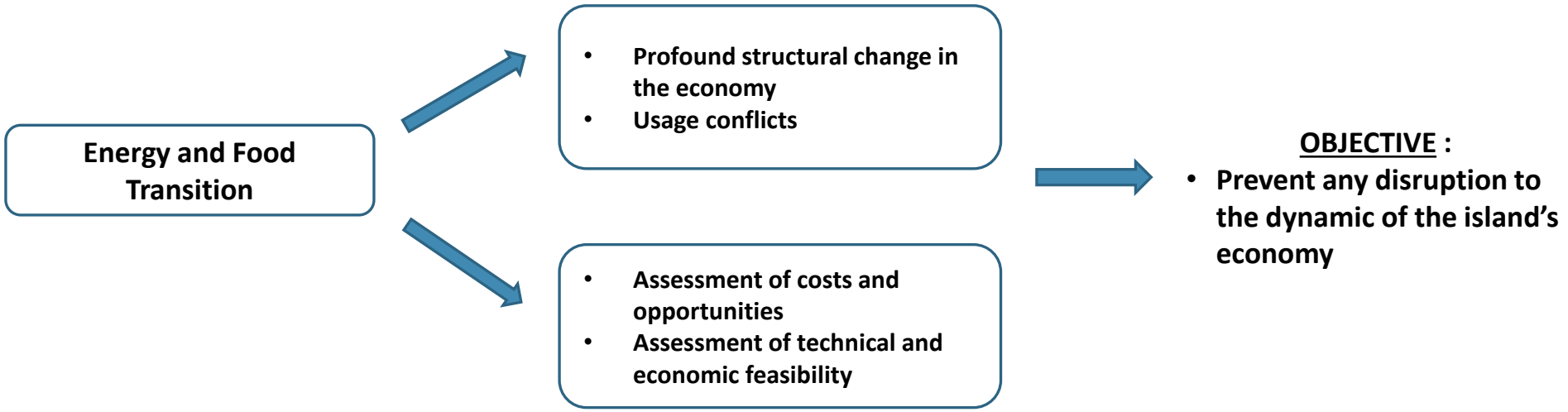
Food Autonomy

Exportation/Subvention

Biomass

Energy Autonomy

General Overview of the work



Research question :

What public policies should be implemented to ensure a proper coordination of this dual energy and food transition?

Methodologies used

#1 . CGE model (Computable General Equilibrium model) - top down

→ Evaluation of the macroeconomic and social impacts of transitions

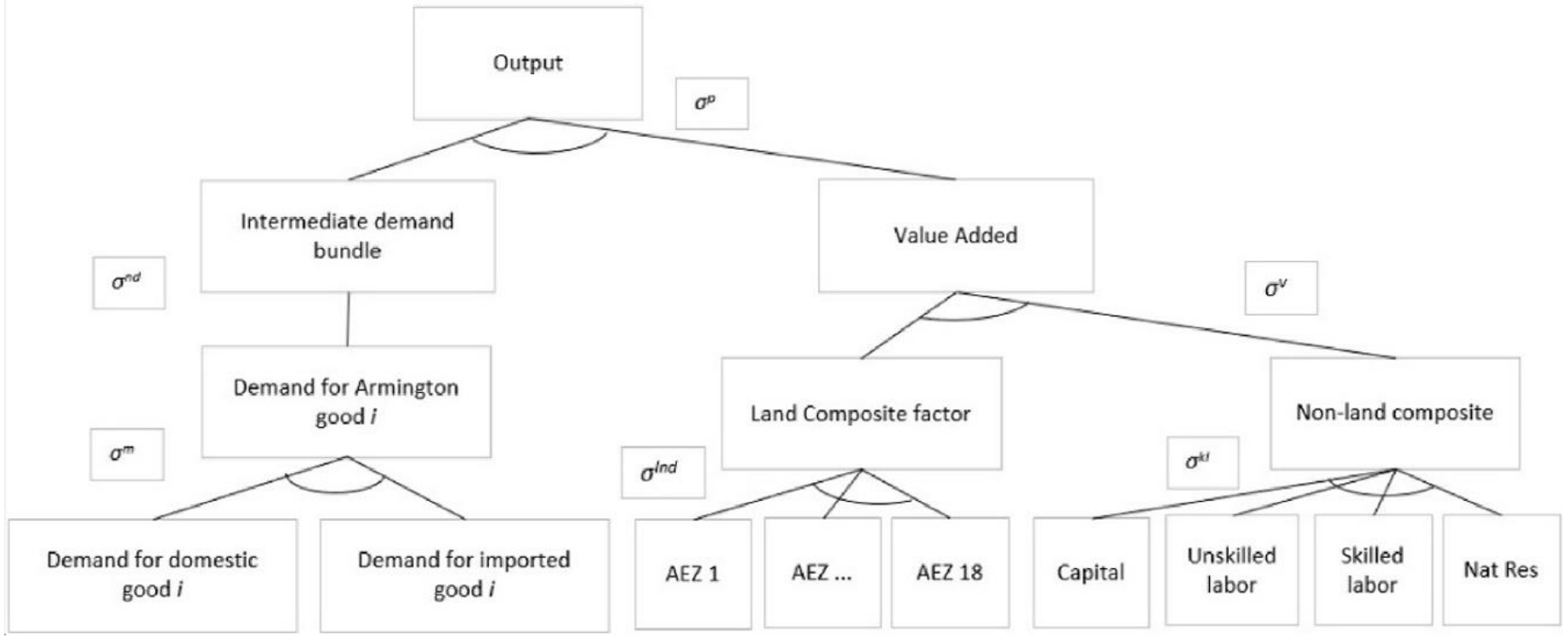
→ **Modèle GetRun-NRJ :** The base model, specific to Reunion Island

#1 . Energy Prospective Model TIMES-Réunion - Bottom up

→ A linear optimization model that minimizes the energy production cost under various constraints

→ Evaluation of the technical, environmental, and economic feasibility of transitions

→ Development of the **Times-Reunion model** : taking into account the entire energy system

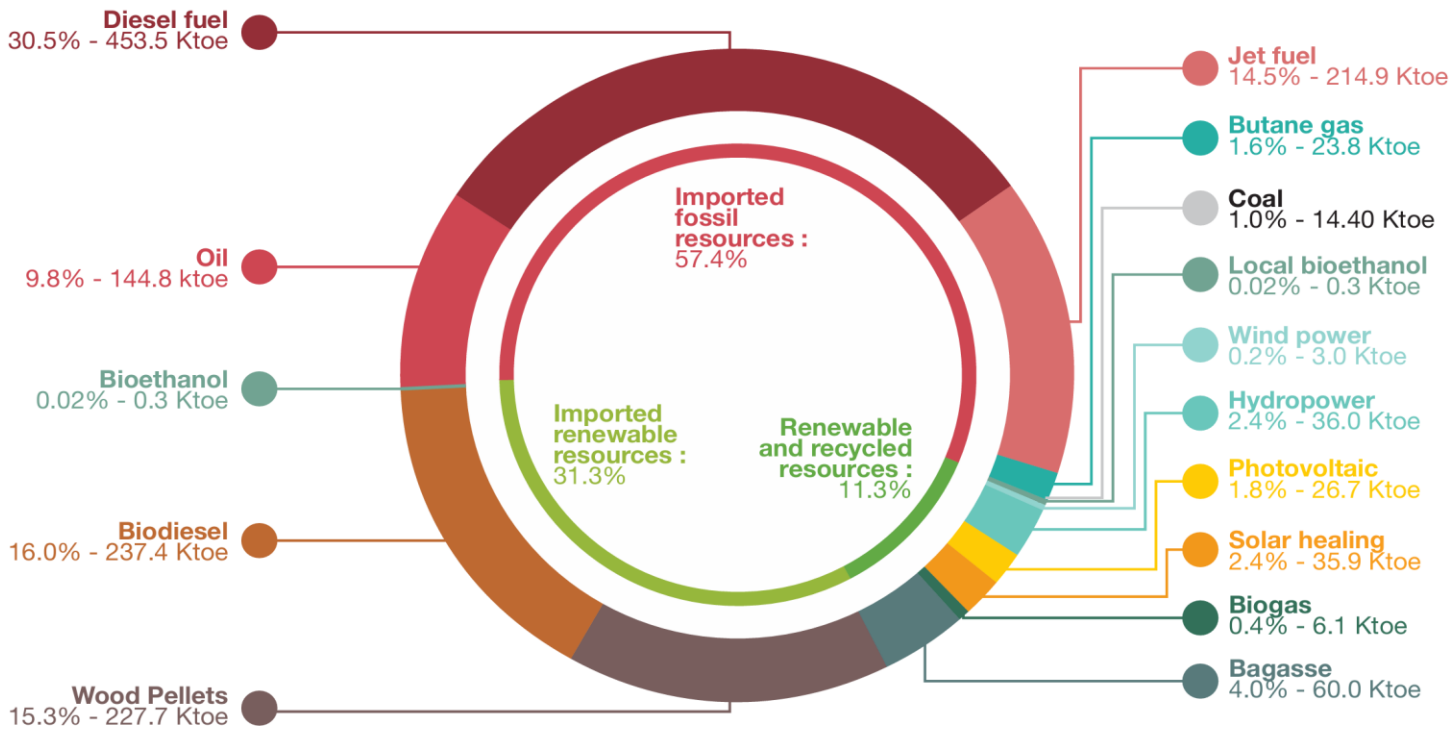


specification in literature

- Structure of production of a CGE Model
- Source : Cordova, J. A. M., & Koo, Y. (2023), Trade-induced land-use transitions and greenhouse gas emissions: The case of the EU-Mercosur free-trade agreement

Dependence on fossil fuels

CONSUMPTION SHARE OF PRIMARY ENERGY IN 2024



Evolution of the energy dependency rate between 2000 and 2024

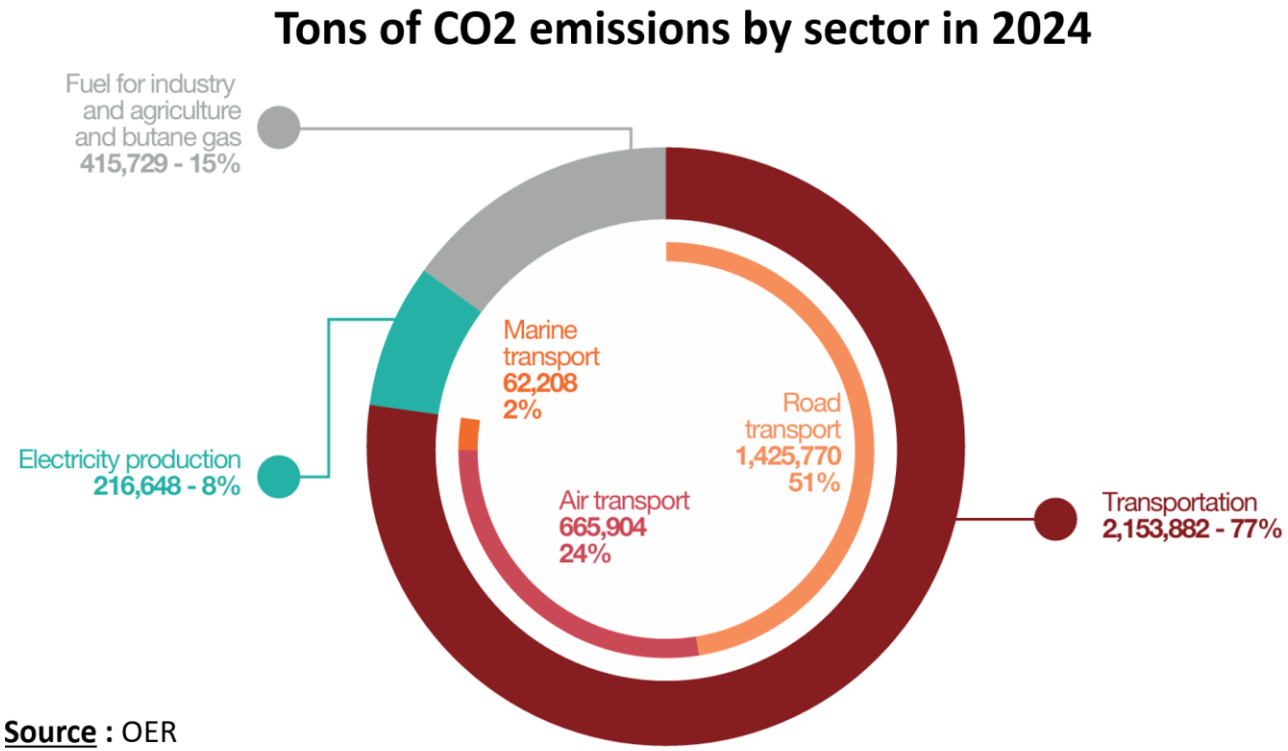
2000	2005	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
83.9%	87.7%	87.4%	88.3%	87.1%	86.1%	86.7%	85.9%	86.4%	86.9%	86.8%	87.2%	86.7%	88.0%	86.7%	88.2%	88.7%

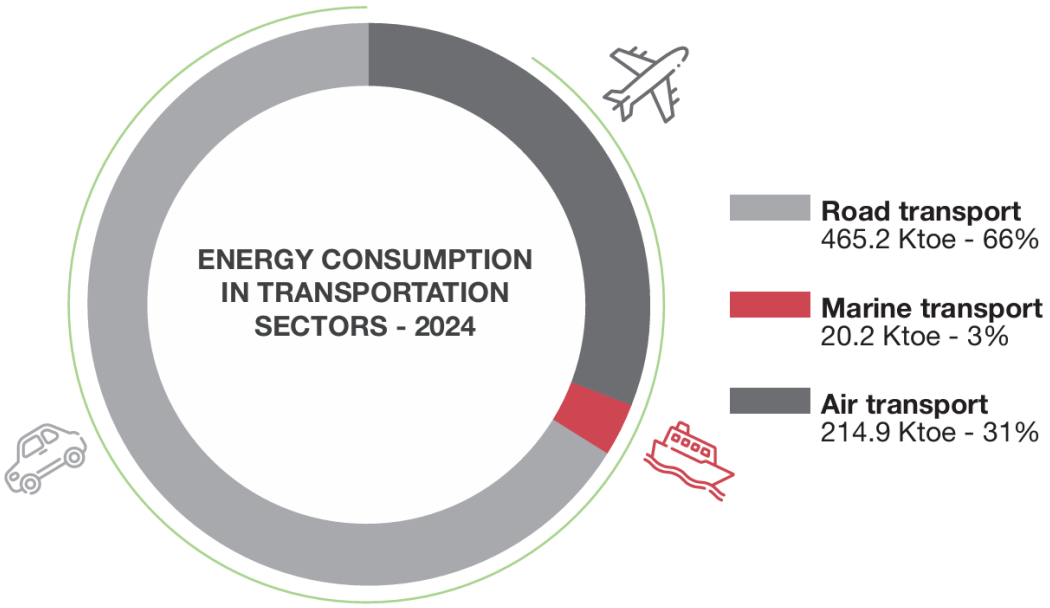
Source: Observatoire Energie Réunion (OER)

Energy consumption on Reunion Island

Comparison :

- Electricity production = **44% of fossil fuel consumption in 2022**
- Transport = **56% of fossil fuel consumption in 2022**





Source : OER

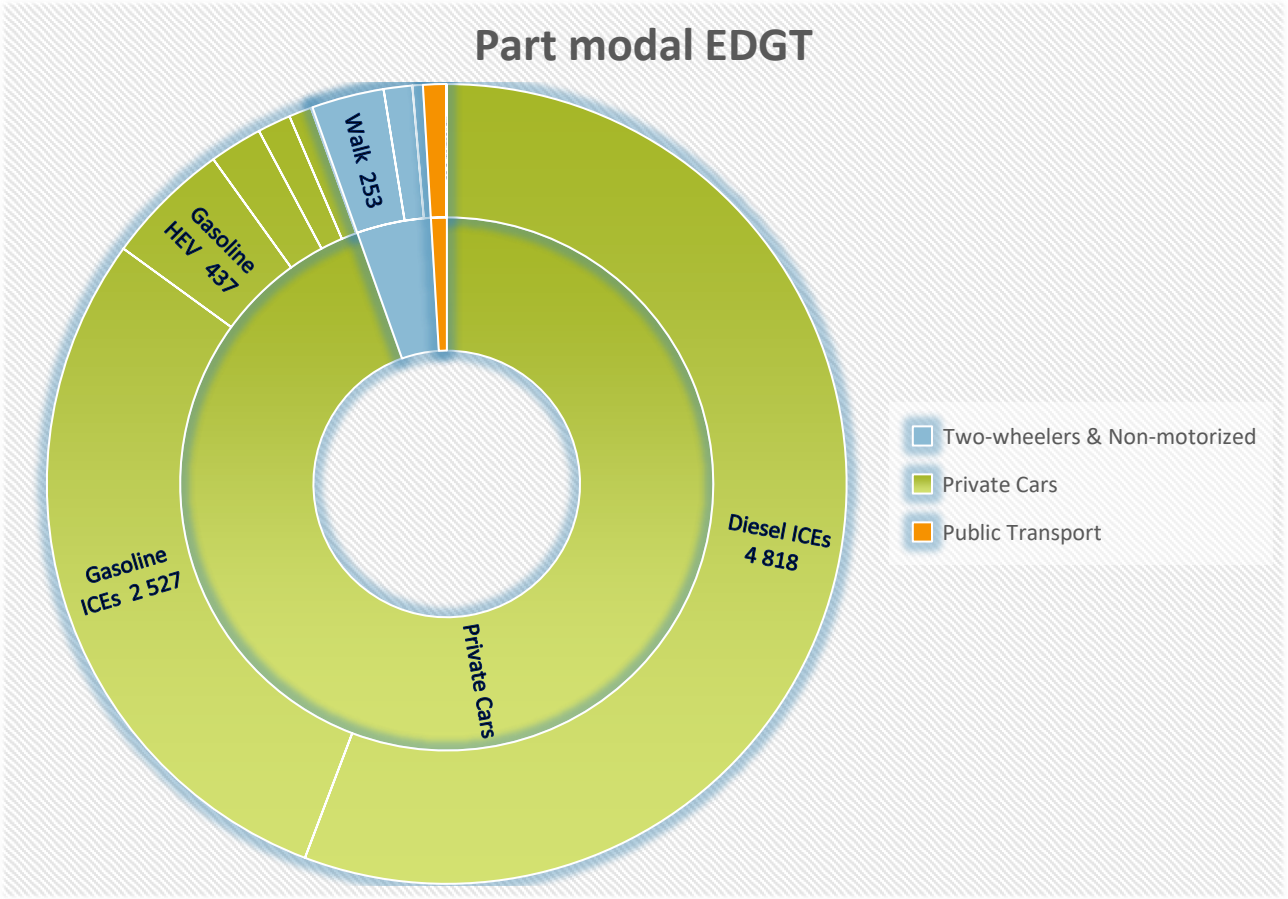
Scenarios

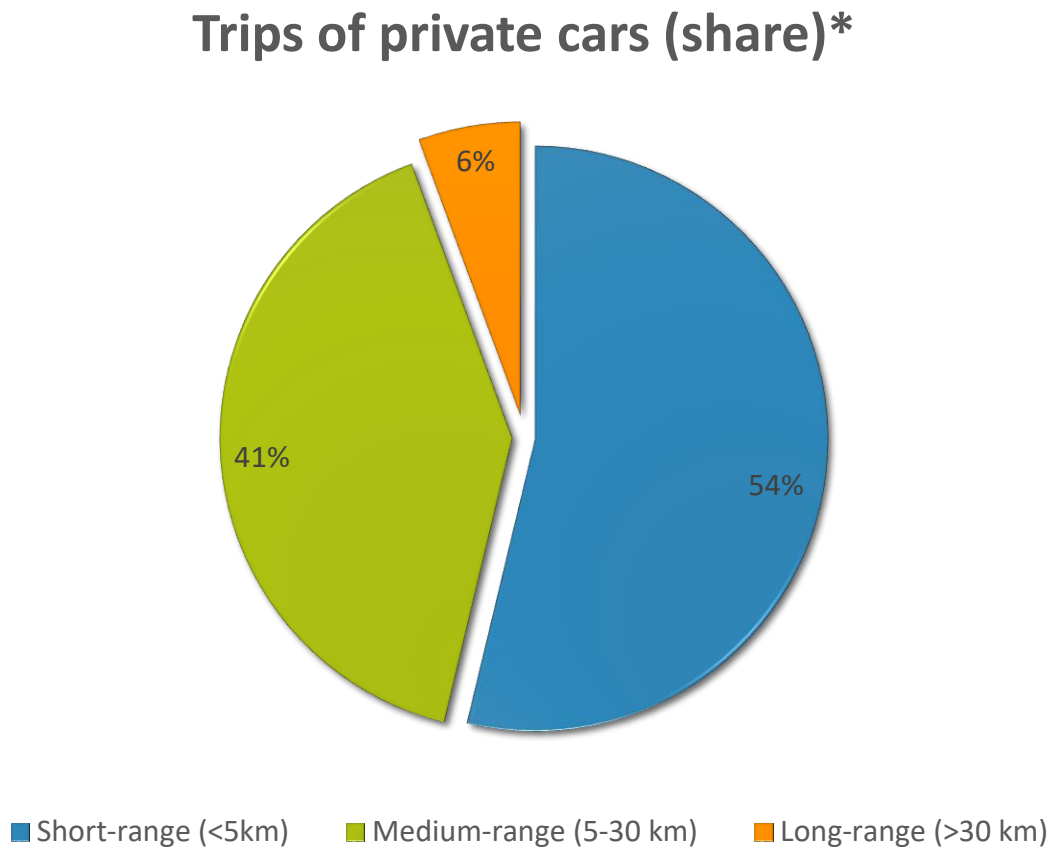
<u>The energy sovereignty of the territory cannot be achieved without</u>:

- a massive integration of local renewable resources into the power mix
- the development of alternative mobility
- the implementation of strong measures to control energy demand

→ The objectives set in La Réunion's **PPE (Multi-year Energy Plan)** should help **reduce the territory's energy dependence to 69% by 2028**

Mobility with private cars





Source : author's calculation

1 – Input Data

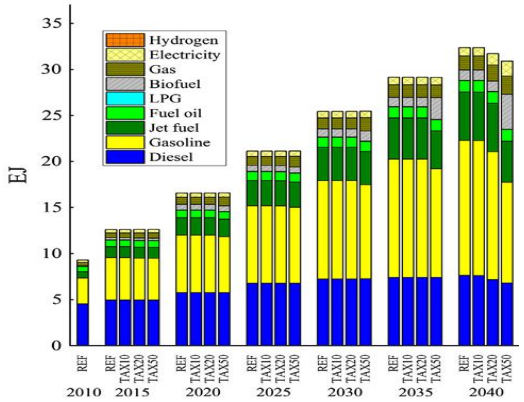
ADEME · EDF · JRC EUROPEAN COMMISSION · IEA International Energy Agency · MINISTÈRE DE LA TRANSITION ÉCOLOGIQUE · SYNDICAT MIXTE DE TRANSPORTS DE LA REUNION · oer observatoire énergie réunion · etsap

2 – Scenarios

TIMES Simulations

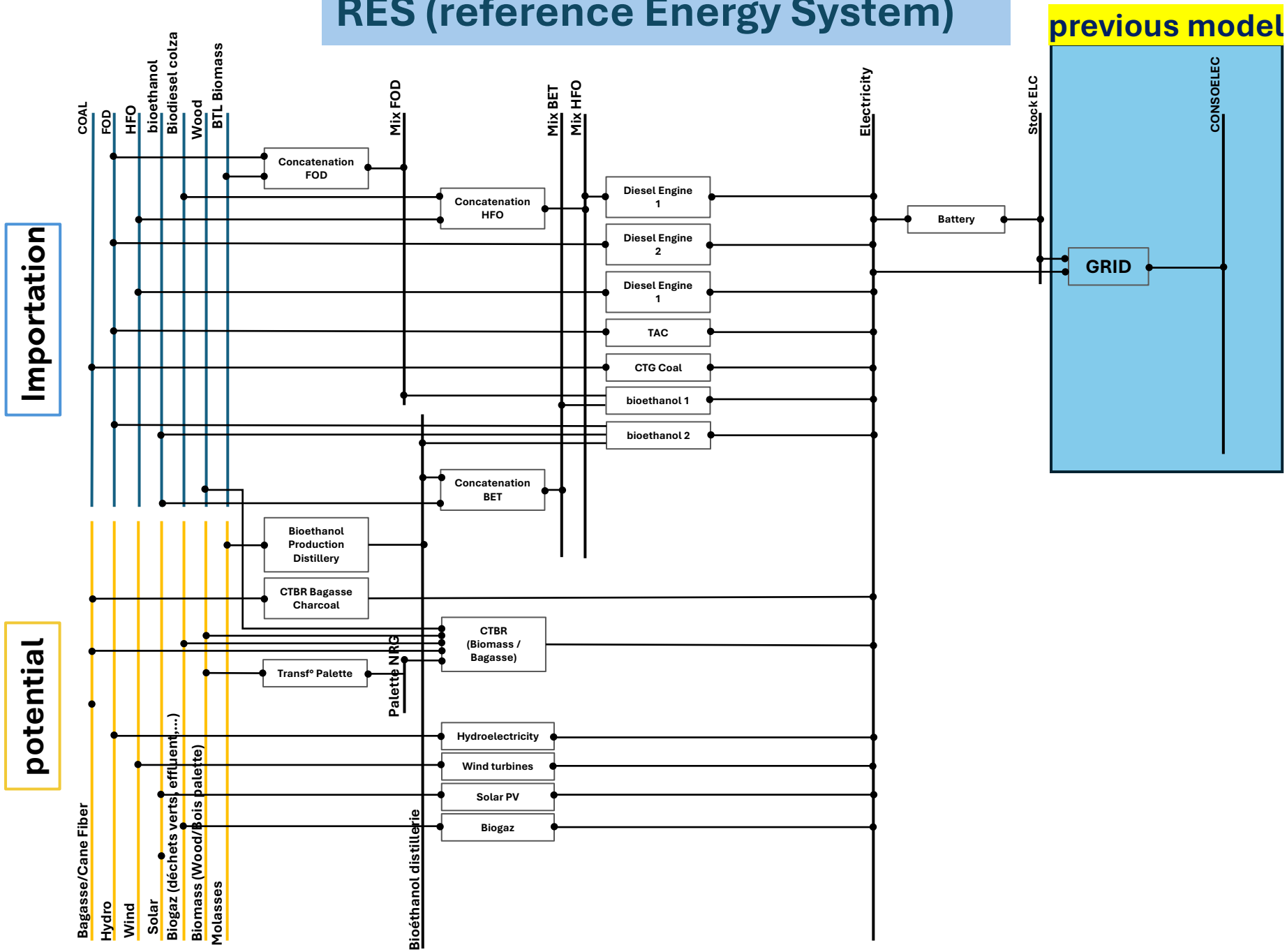
$$\min \quad c^T x$$
$$\text{s.t.} \quad Ax \leq b$$
$$x \geq 0$$

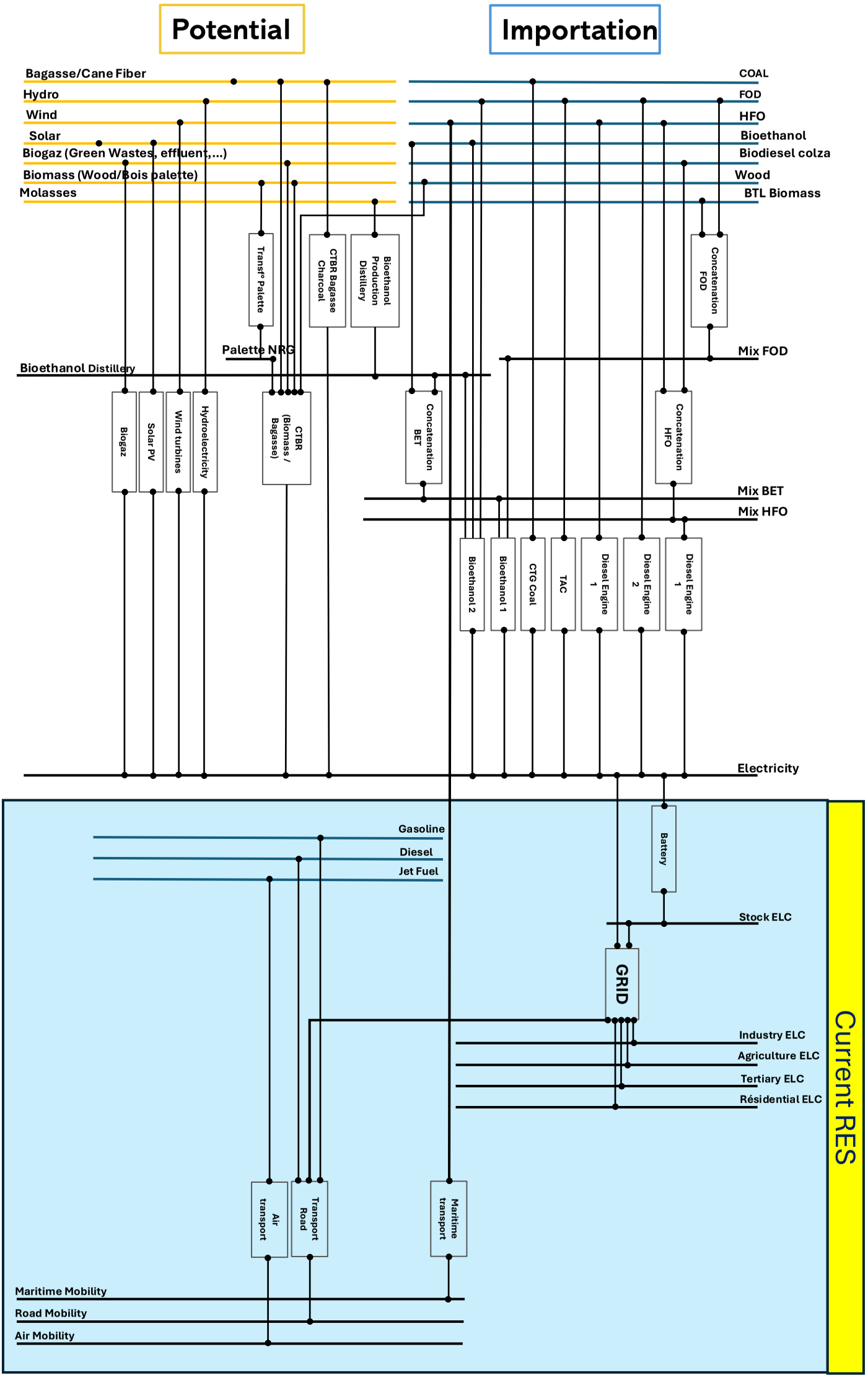
Results



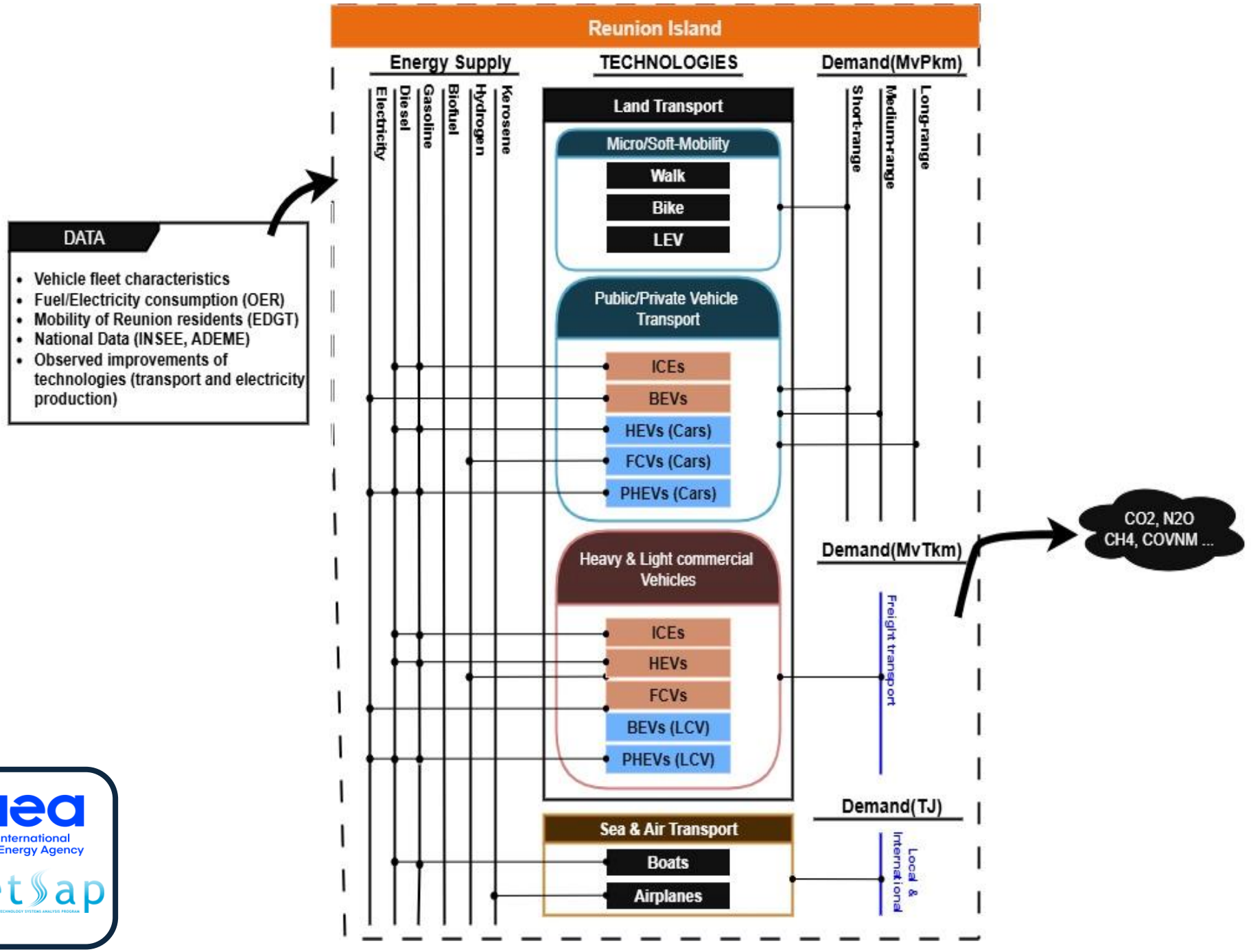
- VRT = Vehicle Registration Tax (Bonus /Malus écologique)
- Modal Shift
- End of ICEs
- Occupancy Rates
- Scenario Azur and Emeraude
- PPE = **multi-year energy plan**

RES (reference Energy System)

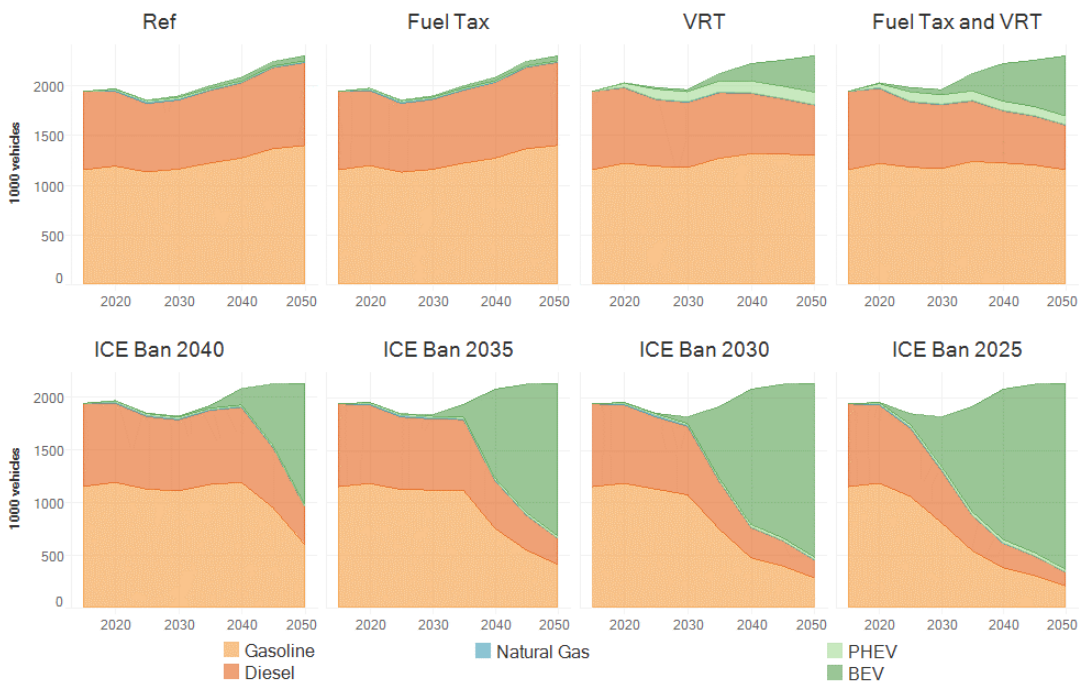



Potential
Importation
Bagasse/Cane Fiber
Hydro
Wind
Solar
Biogaz (Green Wastes, effluent,...)
Biomass (Wood/Bois palette)
Molasses
COAL
FOD
HFO
Bioethanol
Biodiesel colza
Wood
BTL Biomass
Transf° Palette
CTBR Bagasse Charcoal
Bioethanol Production Distillery
Concatenation FOD
Palette NRG
Mix FOD
Bioethanol Distillery
Biogaz
Solar PV
Wind turbines
Hydroelectricity
CTBR (Biomass / Bagasse)
Concatenation BET
Concatenation HFO
Mix BET
Mix HFO
Bioethanol 2
Bioethanol 1
CTG Coal
TAC
Diesel Engine 1
Diesel Engine 2
Diesel Engine 1
Electricity
Gasoline
Diesel
Jet Fuel
Battery
Stock ELC
GRID
Industry ELC
Agriculture ELC
Tertiary ELC
Résidential ELC
Air transport
Transport Road
Maritime transport
Maritime Mobility
Road Mobility
Air Mobility
Current RES

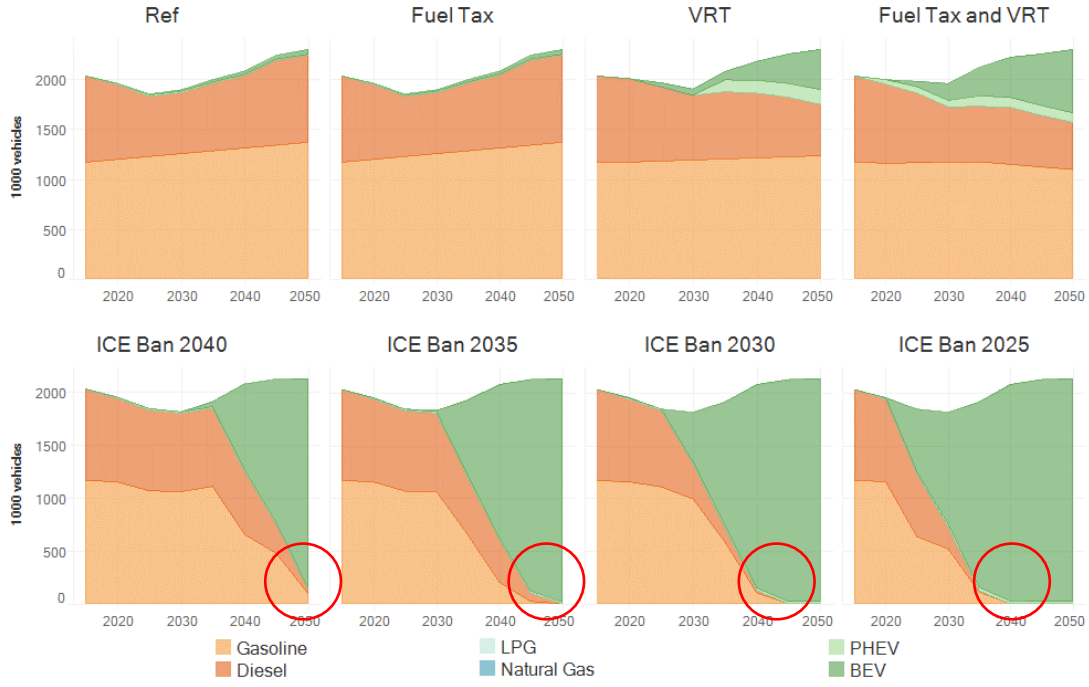
Reference Energy System of transport



DCSM



TIMES-DKMS



Source: Tattini, J., & Gargiulo, M. (2018). Integrating realistic technology's retirement profile in TIMES models - The case of the Danish car sector

Retirement Profile

Essence Thermique		ICE_GSL														
carburant	Age	code	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Essence thermique	0	04	5167	5282	4230	4244	4988	7048	9308	11847	13967	15622	12777	12684	11139	10423
Essence thermique	1	04	5191	5146	5256	4224	4225	5004	7093	9144	11677	13782	15584	12732	12528	10951
Essence thermique	2	04	5671	5194	5184	5287	4269	4279	5060	7105	9150	11668	13766	15715	12673	12369
Essence thermique	3	04	7135	5665	5231	5190	5337	4281	4294	5084	7128	9200	11684	13882	15749	12596
Essence thermique	4	04	6989	6869	5435	5071	5069	5058	4091	4114	4864	6755	8766	11126	13055.651	14241.742
Essence thermique	5	04	9159	6933	6841	5457	5097	5079	5071	4115	4068	4867	6814	8808	11147	12931.822
Essence thermique	6	04	8645	8781	6689	6646	5323	5062	5062	5032	4049	4110	4875	6771	8823	10998.936
Essence thermique	7	04	9166	8445	8584	6641	6618	5323	5044	5050	4994	4068	4137	4857	6779	8720.826
Essence thermique	8	04	9284	8763	8231	8387	6517	6477	5230	4981	4949	4896	4047	4083	4837	6605.789
Essence thermique	9	04	11071	8956	8515	8013	8262	6436	6329	5118	4882	4881	4826	3973	4063	4770.027
Essence thermique	10	04	9958	10460	8490	8193	7774	8068	6282	6166	4913	4724	4786	4706	3900	3944.769
Essence thermique	11	04	10801	9344	9861	8176	7890	7588	7846	6126	5930	4799	4660	4656	4675	3822.294
Essence thermique	12	04	8683	9845	8712	9333	7794	7612	7258	7495	5776	5600	4653	4486	4548	4538.489
Essence thermique	13	04	6785	7944	9046	8252	8855	7415	7241	6922	6976	5396	5366	4490	4375	4408.468
Essence thermique	14	04	6728	6008	7152	8402	7683	8271	7033	6744	6339	6377	5071	5063	4300	4158.919
Essence thermique	15	04	4169	5877	5295	6544	7896	7188	7723	6528	6104	5778	5869	4800	4831	4082.906
Essence thermique	16	04	3535	3459	5118	4670	5899	7229	6625	7074	5764	5466	5282	5382	4458	4570.26
Essence thermique	17	04	2673	2929	2997	4571	4185	5344	6536	6030	6153	5065	4907	4824	4944	4149.457
Essence thermique	18	04	2702	2219	2376	2623	4035	3769	4794	5813	5156	5220	4479	4353	4365	4522.859
Essence thermique	19	04	1765	2260	1809	2052	2257	3617	3370	4240	4958	4360	4526	3951	3858	3958.95
Essence thermique	20	04	1445	1429	1857	1550	1762	1978	3169	2966	3538	4073	3727	3928	3534	3465.496
Essence thermique	21	04	1109	1190	1133	1595	1331	1481	1674	2735	2435	2862	3468	3219	3424	3113.742
Essence thermique	22	04	820	878	978	1032	1380	1143	1282	1424	2177	1901	2380	2936	2806	2997.953
Essence thermique	23	04	458	655	738	846	894	1172	949	1125	1155	1664	1524	1964	2532	2446.03
Essence thermique	24	04	286	372	543	642	749	758	1002	801	883	848	1355	1313	1658	2183.523

- **There are cars that remain in the fleet for more than 15 years**
- **Need to create the retirement profile for each technologies**

Retirement Profile

Survival Rates for Gasoline ICE																
carburant	Age	code	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Mean Sur RATES
Essence thermique	0	04	0.995935746	0.995077622	0.99858156	0.995523091	1.003207698	1.00638479	0.982380748	0.985650376	0.986754493	0.997567533	0.996478046	0.987701041	0.983122363	0.993412701
Essence thermique	1	04	1.000577923	1.007384376	1.005898021	1.010653409	1.012781065	1.011191047	1.001691809	1.000656168	0.999229254	0.998839065	1.008406057	0.995366007	0.987308429	1.003075587
Essence thermique	2	04	0.998941986	1.007123604	1.001157407	1.009457159	1.002810963	1.003505492	1.004743083	1.003237157	1.005464481	1.001371272	1.008426558	1.002163538	0.993924091	1.003255907
Essence thermique	3	04	0.962718991	0.959399823	0.969413114	0.976685934	0.94772344	0.955617846	0.958081043	0.956726987	0.947671156	0.952826087	0.952242383	0.940473347	0.904295003	0.952605781
Essence thermique	4	04	0.991987409	0.995923715	1.004047838	1.005127194	1.001972776	1.002570186	1.005866536	0.988818668	1.000616776	1.008734271	1.004791239	1.001887471	0.990515295	1.000219952
Essence thermique	5	04	0.958729119	0.964806	0.971495395	0.975444383	0.993133216	0.996652884	0.992309209	0.983961118	1.010324484	1.001643723	0.993689463	1.001702997	0.986717144	0.986969934
Essence thermique	6	04	0.97686524	0.977565198	0.992824039	0.99578694	1	0.996444093	0.997629395	0.992448331	1.004692517	1.006569343	0.996307692	1.001181509	0.988419585	0.994364145
Essence thermique	7	04	0.956033166	0.974659562	0.977050326	0.981328113	0.97869447	0.982528649	0.987509913	0.98	0.980376452	0.994837758	0.986947063	0.995882232	0.974448886	0.980792045
Essence thermique	8	04	0.964670401	0.97169919	0.973514761	0.985095982	0.987570968	0.977149915	0.978585086	0.980124473	0.98625985	0.985702614	0.981714851	0.995101641	0.986154021	0.981026443
Essence thermique	9	04	0.944810767	0.947967843	0.962184381	0.970173468	0.976519003	0.976072094	0.974245536	0.959945291	0.967636215	0.980536775	0.975134687	0.981625975	0.970900566	0.968288662
Essence thermique	10	04	0.938341032	0.942734226	0.963015312	0.96301721	0.976074093	0.972483887	0.975167144	0.961725592	0.976796255	0.986452159	0.972837443	0.993412665	0.980075385	0.9693948
Essence thermique	11	04	0.911489677	0.932363014	0.946455735	0.953277886	0.964765526	0.956510279	0.955263829	0.942866471	0.944350759	0.969576995	0.962660944	0.976804124	0.970799786	0.952860387
Essence thermique	12	04	0.914891167	0.918842052	0.947199265	0.948783885	0.951372851	0.951261167	0.953706255	0.930753836	0.934210526	0.958214286	0.964968837	0.975256353	0.969320141	0.947598509
Essence thermique	13	04	0.885482682	0.900302115	0.928808313	0.931047019	0.93404856	0.948482805	0.931363071	0.915775787	0.914134174	0.9397702	0.943533358	0.957683742	0.950610057	0.929310914
Essence thermique	14	04	0.873513674	0.8813249	0.914988814	0.939776244	0.935572042	0.933744408	0.928195649	0.90510083	0.911500237	0.920338717	0.946558864	0.954177365	0.949513023	0.922638828
Essence thermique	15	04	0.829695371	0.870852476	0.881964117	0.90143643	0.915526849	0.921675014	0.915965298	0.882965686	0.895478375	0.914157148	0.917021639	0.92875	0.946027738	0.901655088
Essence thermique	16	04	0.828571429	0.866435386	0.893122313	0.89614561	0.905916257	0.904136118	0.910188679	0.869804919	0.878730049	0.897731431	0.91329042	0.918617614	0.930788919	0.89334455
Essence thermique	17	04	0.830153386	0.811198361	0.875208542	0.882739007	0.900597372	0.897080838	0.889381885	0.855058043	0.84836665	0.884304047	0.887100061	0.904850746	0.914817759	0.875450515
Essence thermique	18	04	0.836417469	0.815232087	0.863636364	0.860465116	0.896406444	0.894136376	0.884438882	0.852915878	0.845616757	0.867049808	0.882116544	0.88628532	0.906975945	0.868591768
Essence thermique	19	04	0.809631728	0.821681416	0.856826976	0.858674464	0.876384581	0.876140448	0.880118694	0.834433962	0.821500605	0.854816514	0.867874503	0.894457099	0.898262312	0.8577541
Essence thermique	20	04	0.823529412	0.792862141	0.858912224	0.858709677	0.840522134	0.846309403	0.86304828	0.820971005	0.8089316	0.85146084	0.863697344	0.871690428	0.881081494	0.844748152
Essence thermique	21	04	0.791704238	0.821848739	0.910856134	0.865203762	0.858752817	0.86563133	0.850657109	0.795978062	0.780698152	0.831586303	0.846597463	0.871699285	0.875570386	0.843598752
Essence thermique	22	04	0.798780488	0.840546697	0.865030675	0.86627907	0.849275362	0.830271216	0.877535101	0.811095506	0.764354616	0.801683325	0.825210084	0.86239782	0.871714184	0.835705703
Essence thermique	23	04	0.812227074	0.829007634	0.869918699	0.88534279	0.84787472	0.854948805	0.844046365	0.784888889	0.734199134	0.814302885	0.861548556	0.844195519	0.862370853	0.834220917
Essence thermique	24	04	1.662587413	1.509408602	1.372928177	1.507009346	1.635514019	1.892480211	1.723552894	2.245942572	2.040770102	2.133254717	1.595940959	1.897943641	1.787960796	1.769637958
Essence thermique	25 (hypothèses)	04	0.768484848	0.7872415	0.885129118	0.865191147	0.844099914	0.780680272	0.802602533	0.694460529	0.667778395	0.669256382	0.79694122	0.768246628	0.793054842	0.778705179

- **We calculate the average survival rate for each specific age**

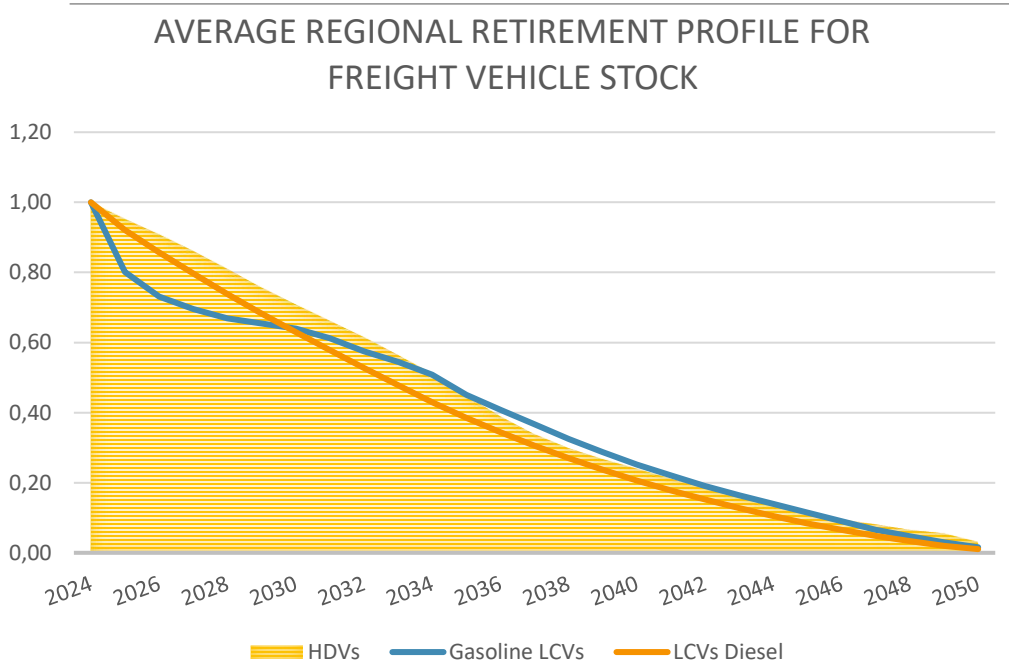
Retirement Profile

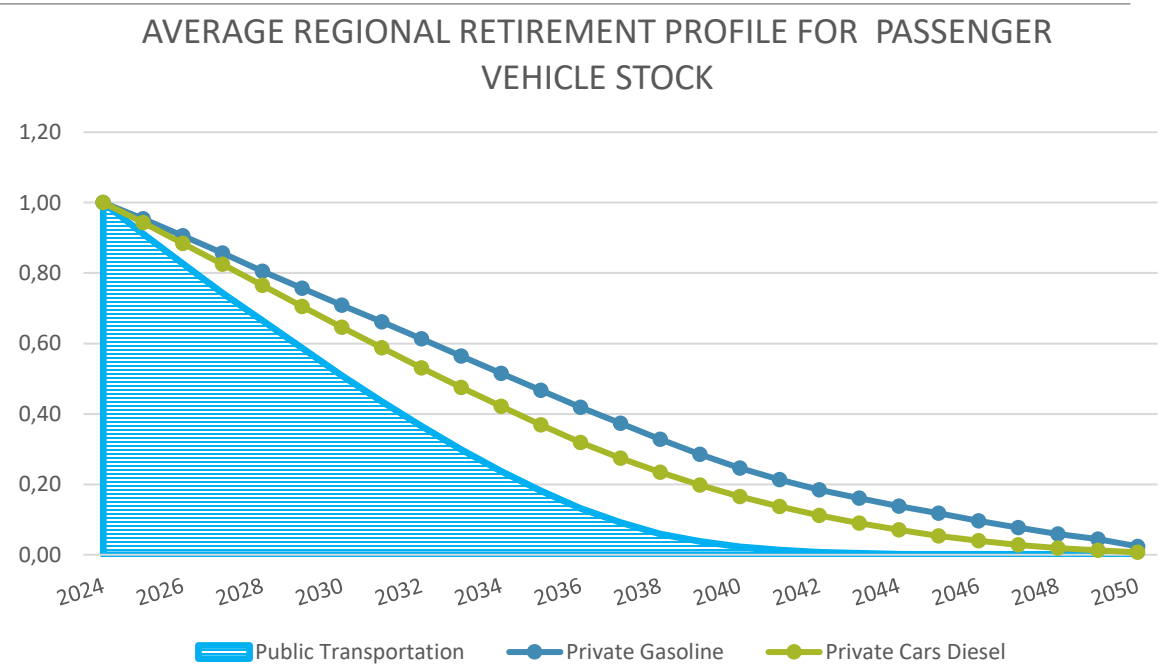
nb de véhicules en 2024

Age	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
0	10423																					
1	10951	10354.3406																				
2	12369	10984.6808	10386.1863																			
3	12596	12409.2723	11020.4459	10420.0027																		
4	14241.742	11999.0224	11821.1445	10498.1404	9926.15482																	
5	12931.822	14244.8745	12001.6616	11823.7446	10500.4495	9928.3381																
6	10998.936	12763.3195	14059.2628	11845.2792	11669.6804	10363.628	9798.97119															
7	8720.826	10936.9476	12691.3873	13980.0269	11778.5209	11603.9118	10305.2201	9743.74561														
8	6605.789	8553.31677	10726.8712	12447.6117	13711.4991	11552.2796	11381.0244	10107.2779	9556.58819													
9	4770.027	6480.45368	8391.02992	10523.3443	12211.4362	13451.3432	11333.0918	11165.0859	9915.50684	9375.26571												
10	3944.769	4618.76306	6274.94982	8124.93913	10189.635	11824.1952	13024.7831	10973.7043	10811.0261	9601.07284	9077.96349											
11	3822.294	3824.03856	4477.40489	6082.90373	7876.27375	9877.77914	11462.3134	12626.157	10637.8518	10480.1525	9307.23009	8800.1306										
12	4538.489	3642.11254	3643.77486	4266.34176	5796.158	7504.98925	9412.14445	10921.9843	12030.9649	10136.3876	9986.12212	8868.49086	8385.29585									
13	4408.468	4300.66541	3451.26041	3452.83562	4042.77909	5492.43068	7111.71662	8918.93405	10349.6561	11400.5244	9605.2258	9462.83444	8403.76872	7945.89384								
14	4158.919	4096.83743	3996.6553	3207.29397	3208.75783	3756.99873	5104.17578	6608.99588	8288.46276	9618.04836	10594.6317	8926.24117	8793.91532	7809.71399	7384.20587							
15	4082.906	3837.18015	3779.90128	3687.46937	2959.17395	2960.52456	3466.35291	4709.31076	6097.71621	7647.25757	8873.98487	9775.01861	8235.69669	8113.60773	7205.54537	6812.95505						
16	4570.26	3681.37297	3459.81301	3408.16722	3324.82552	2668.15425	2669.37204	3125.45474	4246.174	5498.03685	6895.18869	8001.27361	8813.69527	7425.75782	7315.67569	6496.91664	6142.93559					
17	4149.457	4082.81686	3288.73448	3090.80509	3044.66761	2970.21475	2383.58105	2384.66896	2792.10795	3793.2964	4911.64125	6159.77924	7147.89417	7873.66663	6633.76028	6535.419	5803.98507	5487.75803				
18	4522.859	3632.64427	3574.30412	2879.12429	2705.84691	2665.45583	2600.27604	2086.70726	2087.65967	2444.35235	3320.84329	4299.89886	5392.58191	6257.62763	6893.00551	5807.52885	5721.43593	5081.10172	4804.26059			
19	3958.95	3928.5181	3155.28491	3104.61114	2500.78366	2350.27635	2315.19299	2258.57836	1812.49675	1813.324	2123.14433	2884.45715	3734.85676	4683.95226	5435.32385	5987.20784	5044.37176	4969.59215	4413.40313	4172.9412		
20	3465.496	3395.8056	3369.70251	2706.45857	2662.99294	2145.05744	2015.95918	1985.86628	1937.30485	1554.67652	1555.3861	1821.13575	2474.15494	3203.5887	4017.67925	4662.17132	5135.55208	4326.83056	4262.68805	3785.61463	3579.35743	
21	3113.742	2927.47134	2868.6005	2846.54997	2286.27588	2249.55836	1812.03331	1702.97779	1677.55687	1636.53469	1313.31012	1313.90953	1538.40106	2090.03782	2706.22563	3393.92713	3938.36061	4338.24813	3655.08212	3600.89785	3197.89096	3023.65557
22	2997.953	2626.74887	2469.61117	2419.94781	2401.346	1928.69948	1897.72463	1528.62904	1436.62994	1415.18489	1380.57862	1107.90678	1108.41244	1297.79322	1763.1533	2282.96857	2863.11269	3322.39609	3659.74071	3083.42272	3037.71294	2697.73683
23	2446.03	2505.40642	2195.18901	2063.86814	2022.36418	2006.81855	1611.82515	1585.93929	1277.484	1200.59984	1182.67808	1153.75743	925.884012	926.3066	1084.57319	1473.47727	1907.88985	2392.7196	2776.54537	3058.46618	2576.83395	2538.63403
24	2183.523	2040.52939	2090.06244	1831.27259	1721.72197	1687.0985	1674.13001	1344.61826	1323.02373	1065.70388	1001.5655	986.614793	962.488582	772.39181	772.744342	904.773643	1229.20556	1591.60162	1996.05674	2316.25222	2551.43646	2149.64878
25 (hypothèses)	2964.439	3864.04518	3610.99826	3698.65383	3240.68948	3046.82456	2985.55355	2962.60401	2379.48751	2341.27302	1885.91003	1772.40832	1745.95099	1703.25633	1366.85386	1367.47772	1601.12178	2175.24881	2816.55865	3532.29778	4098.92785	4515.11881
26 (hypothèses)	1976.292667	2308.424	3008.952	2811.90305	2880.16089	2523.54168	2372.57806	2324.86601	2306.99509	1852.91924	1823.16142	1468.56791	1380.18354	1359.58108	1326.33452	1064.37618	1064.86198	1246.80182	1693.87751	2193.2688	2750.61857	3191.85635
27 (hypothèses)	988.1463333	1154.212	1348.18629	1757.31488	1642.2326	1682.09715	1473.82123	1385.65412	1357.7889	1347.35177	1082.15836	1064.77893	857.686079	806.067051	794.034619	774.617673	621.626435	621.910155	728.168279	989.273395	1280.93233	1606.4407
28 (hypothèses)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	166901.135	159193.82	151161.375	142978.61	134304.426	126240.215	118211.841	110451.76	102322.482	94221.9624	85920.7239	77867.204	69900.8663	62269.2425	54699.1153	47563.8169	41074.4593	35554.2087	30806.3811	26732.4348	23073.7105	19723.0911
Remaining compared to base year		0.95382108	0.90569411	0.85666649	0.80469451	0.75637721	0.70827464	0.66177956	0.61307242	0.56453758	0.51480012	0.46654688	0.418816	0.37309059	0.32773363	0.28498199	0.24610054	0.21302557	0.18457862	0.16016928	0.13824777	0.1181723

- **Retirement profile**

Fleet retirement modeling



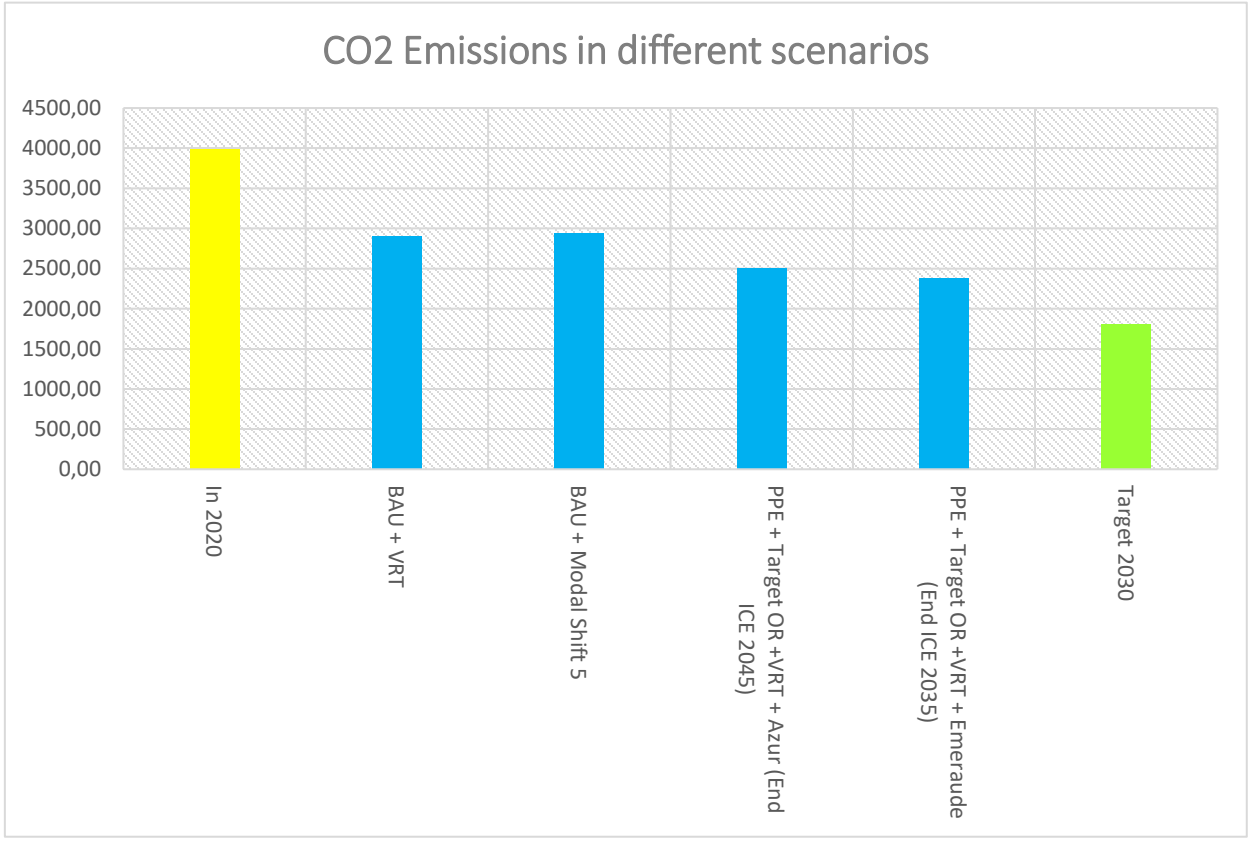


VEDAS's Input :

~TFM_INS				
Attribute	**Year**	**Other_Indexes**	**RE**	**Pset_PN**
SHAPE	1	2	1	
SHAPE	2	2	0,95	
SHAPE	5	2	0,8	
SHAPE	10	2	0,56	
SHAPE	15	2	0,33	
SHAPE	20	2	0,16	
NCAP_CPX	2025		2	TCAR_ICE_GSL22
NCAP_CPX	2050		2	TCAR_ICE_GSL22
NCAP_CPX	0		1	TCAR_ICE_GSL22

~TFM_INS				
Attribute	**Year**	**Other_Indexes**	**RE**	**Pset_PN**
SHAPE	2025		25	TCAR_ICE_DSL22

First Results



CONCLUSIONS:

1. **The adopted options make it possible to better represent the retirement of the vehicle fleet**

2. **The proposed policy measures could lead to a significant reduction in emissions if the PPE targets are met**

3. **Nevertheless, the intended CO2 emission reductions still require more effective measures.**

4. **Other specifications of investment behaviors are necessary: Substitution elasticity, hurdle rates**

THANK YOU FOR YOUR ATTENTION

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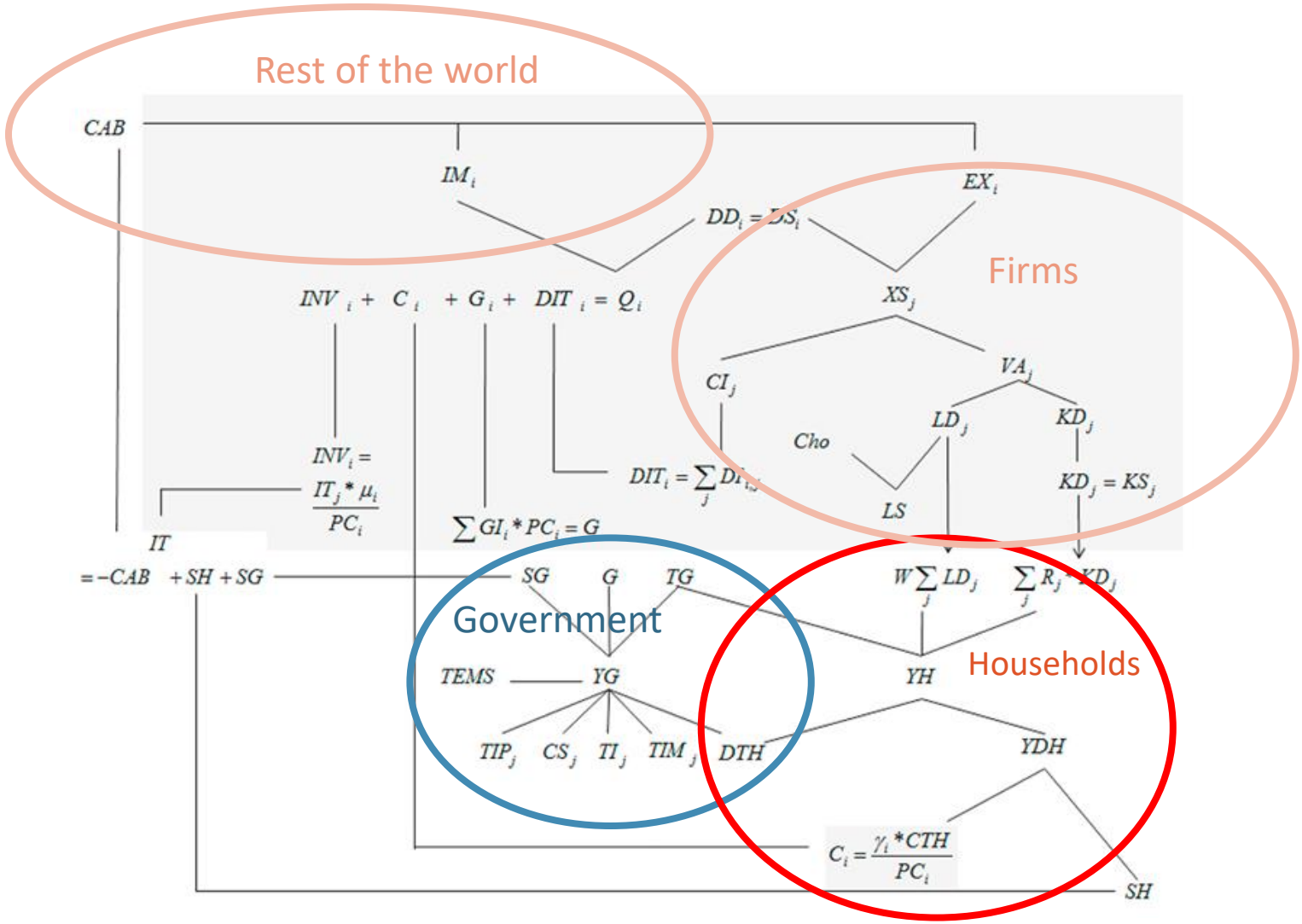
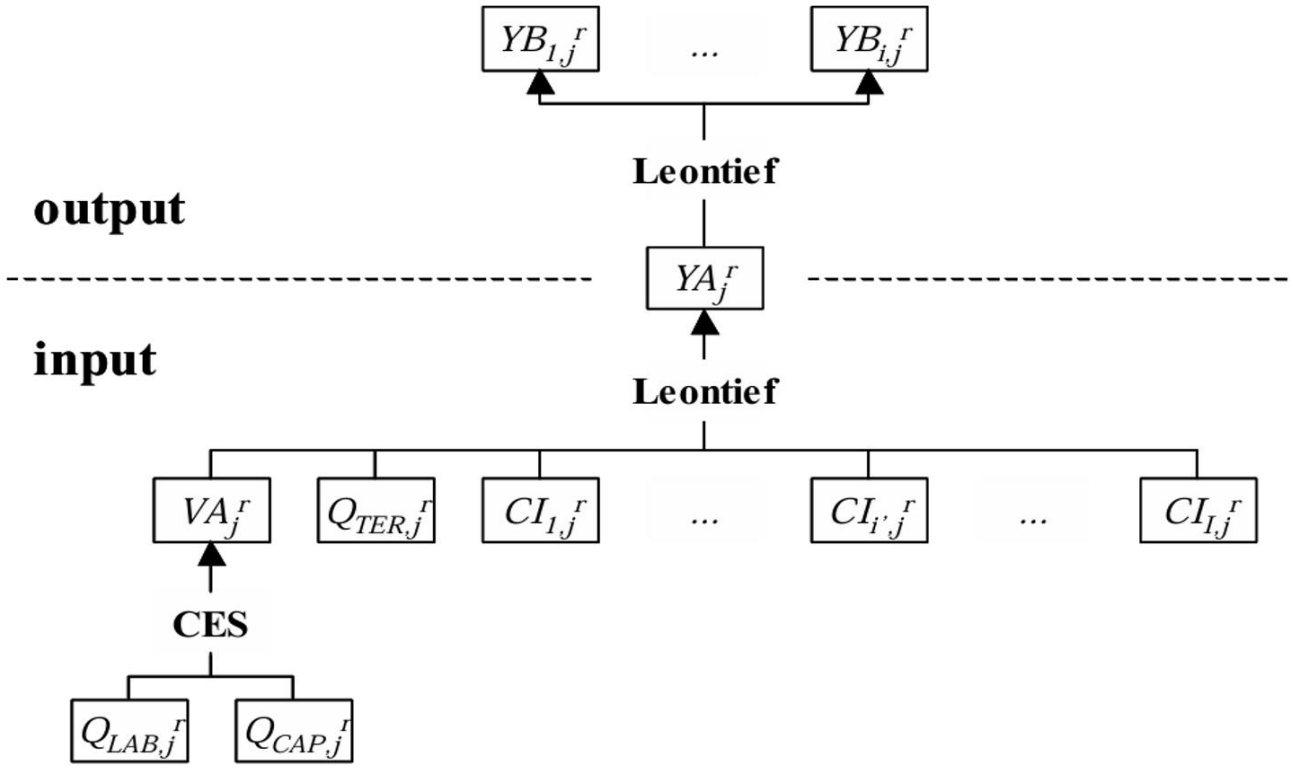
Annex

Interdependence mechanism in a CGE Model





other specifications in literature

Source : Spatialization of a CGE model for studying the location of agricultural activities at a sub-national scale

Puissance (MW)		2024	2029	2033	2040
Azur	Thermique fossile	118	118	80	41
	Biomasse, biogaz, bioéthanol	415	415	415	205
	Hydraulique	136	140	140	140
	Energies renouvelables non synchrones	271	433	564	774
	Autres énergies renouvelables	0	17	17	17
	Stockage	5	25	25	25
Emeraude	Thermique fossile	118	0	0	0
	Biomasse, biogaz, bioéthanol	415	536	536	325
	Hydraulique	136	146	146	146
	Energies renouvelables non synchrones	271	584	803	1 142
	Autres énergies renouvelables	0	19	24	29
	Stockage	5	25	25	25

Tableau 11 : puissances installées au 1er juillet dans les scénarios Azur et Emeraude[2]