Calculation memory report for ECO_2-ferries Project (2024-26)

Ellen Ferry BTM system methodology and performance report

Leading Partner:

Centre for Industrial Mechanics

Syddansk Universitet (SDU, Sønderborg)

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Nomenclature

BL	Baseline
BTM	Battery thermal management
CO2e	Equivalent CO2 emission
GWP	Global warming potential
HP	Heat pump
L	Layout
r	Payback ratio
TEWI	Total equivalent warming impact
T_{out}	Outdoor temperature (Ambient temperature)

This calculation report is developed within the framework of the ECO2-ferries project, an initiative dedicated to advancing the maritime sector toward true zero-emission operations. The core objective of the project is to design and implement an integrated, reversible CO_2 (R744) heat pump system tailored specifically for 100% electric-powered ferries. By replacing conventional synthetic refrigerants (R410a) with natural carbon dioxide and optimizing both thermal battery management and waste heat recovery, the ECO2-ferries project aims to extend the operational range of electric vessels while completely eliminating the greenhouse gas emissions associated with traditional refrigerant leaks.

1. Technical parameters and operational baseline

Technical parameters of Ellen Ferry were obtained from the full evaluation report of the e-ferry [1] and they are summarized on Table 1.

Table 1. Particulars of the E-ferry

Propulsion engines capacity, P_{prop} [kW]	2x700
Nominal battery capacity [MWh]	4.3
Service speed, v_{nom} [knots]	14
Average energy per trip [kWh]	1600
Trip distance, d_{trip} [nm]	22

The vessel’s operational envelope is defined by a 700-kW propulsion baseline. These parameters establish the foundational requirements for the thermal management systems and serve as the ground truth for all energy conservation and driving range extension modeling.

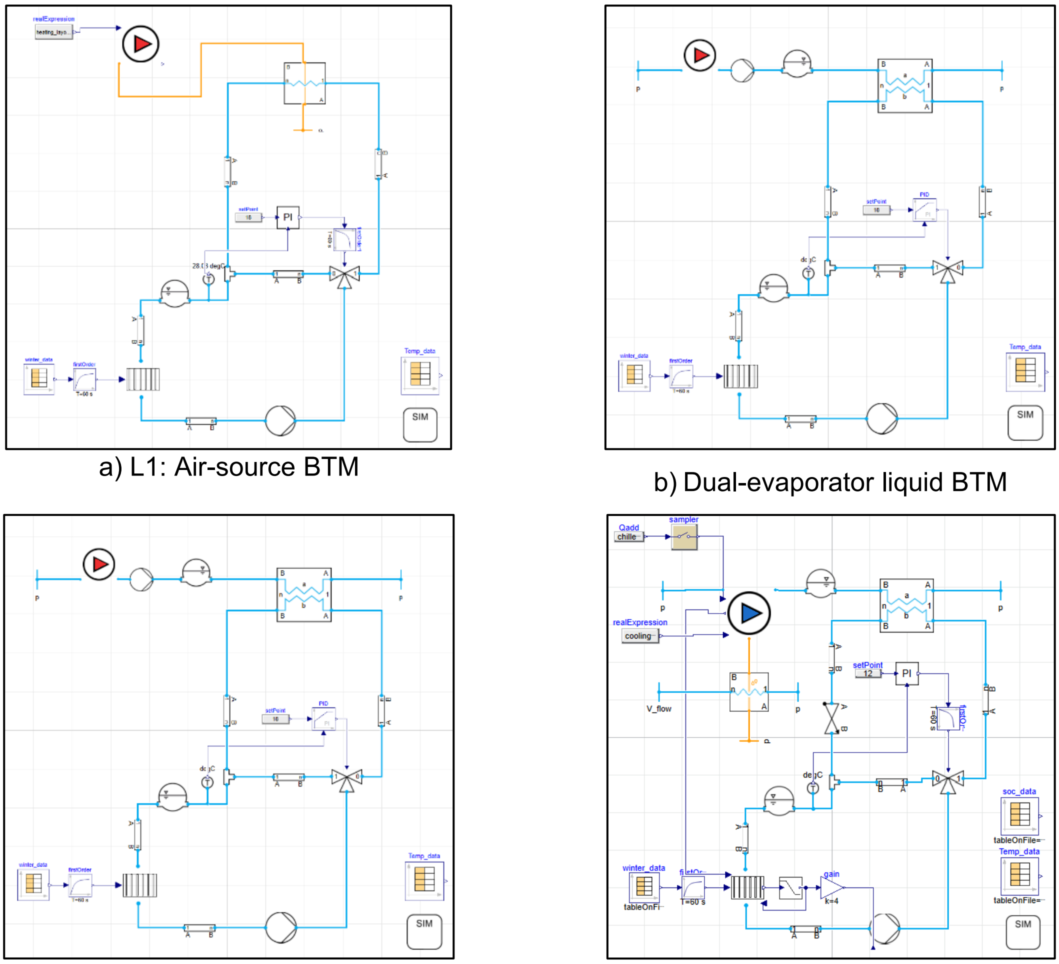
The air condition unit consists of three (3) complete inverter-controlled heat pumps suitable for outdoor marine environment, Climaveneta I-KIR-MTD/0075t air-cooled reversible R410a heat pump complete with inverter-controlled compressor, automation, circulation pump, expansion tank, safety devices and fully assembled switchboard incl. microprocessor control. The needed cooling and heating capacity are 15 kW and 20.4 kW, respectively [2].

2. Methodology

The analysis evaluates the performance of natural refrigerant R744 transcritical heat pumps against the conventional R410a baseline. The primary focus is the efficiency gain derived from Integrated battery thermal management (BTM) architecture.

We evaluated four architecture layouts and the baseline BL (Figure 1):

L1: R744 HP – BTM through a radiator (air finned tube heat exchanger to water battery loop). Only in winter
L2: R744 HP – BTM through chiller (a plate heat exchanger as dual parallel evaporator). In winter and summer
L3: R744 HP – BTM through chiller integrated to the thermal storage system, working in summer.
L4: L2 plus Waste heat recovery (air finned tube heat exchanger to water battery loop). Only in summer
BL: R410a not integrated with the BTM by sea water.



a) L1: Air-source BTM

b) Dual-evaporator liquid BTM

c) Chiller + thermal storage

d) Dual-evaporator + Air-source (WHR)

Figure 1. BTM layouts diagrams depicted in the Dymola environment.

2.1 COP estimation

The Coefficient of Performance (COP) is derived by mapping heating and cooling demands across the operational temperature spectrum. For the R744 configurations, the system utilizes a transcritical cycle to manage high thermal rejection temperatures. The efficiency is governed by the standard ratio:

$$COP = \frac{Required\ thermal\ load\ [kW]}{energy\ consumption\ by\ compressor\ [kW]} \qquad \text{Eq. 1}$$

2.2 Ambient temperature and load mapping

BTM layouts allow for the recovery of waste heat or integrated cooling loops. As shown in the data below, COP values fluctuate significantly based on the load. The load demand was estimated through a load curve for summer and heating, based on the design specifications.
The ambient temperature is a high dynamic parameter. However, to estimate the year energy consumption, the load is estimated on a hourly basis with average ambient temperature.

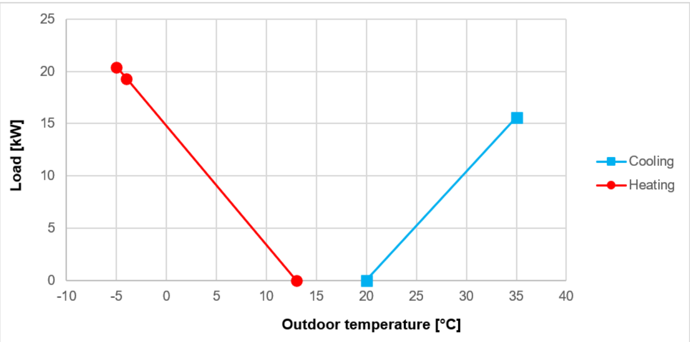


Figure 2. Load profiles in heating and cooling modes.

2.3 Operational availability and hours distribution

Annual energy consumption is aggregated based on temperature bin frequency. The calculation incorporates an operational availability factor AF = **0.995** to adjust simulation results to actual vessel service time and having in account the lack of information about the behavior of the thermal storage system.
We used two approaches: 1) Average monthly ambient temperature and 2) hour distribution frequency.

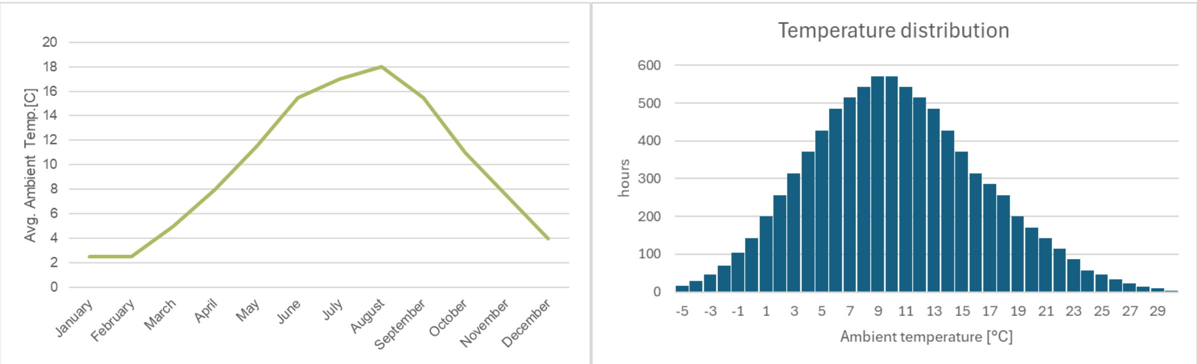


Figure 3. Average ambient temperature distribution, monthly and hourly trough a year.

However, the average monthly values do not show extreme values (-5 °C, 30°C) than can be important in terms of accuracy.

3. Calculation of Energy Consumption and Savings

3.1 Comparative energy consumption analysis

By integrating BTM layouts, significant reductions in annual energy consumption are achieved. The models in the software Dymola were simulated to estimate the electrical consumption during a round trip.

Table 2. Energy consumptions of the different BTM layouts, baseline and R744 heat pump for each outdoor temperature

T_{out} [°C]	Electric consumption [kW]					
	R744	**R744 + L1**	**R744 + L2**	**R744 + L3**	**R744 + L4**	**BL**
-5	10.16	9.01	9.17	9.01	9.17	10.62
-4	9.42	8.38	8.43	8.38	8.43	9.85
-3	8.71	6.86	7.72	6.86	7.72	9.12
-2	8.02	5.73	7.03	5.73	7.03	8.43
-1	7.40	5.14	6.41	5.14	6.41	7.61
0	6.82	4.99	5.83	4.99	5.83	6.86
1	6.13	4.43	6.13	4.43	5.14	6.32
2	5.50	4.45	5.50	4.45	4.51	5.80
3	4.86	3.85	4.86	3.85	3.87	5.34
4	4.35	3.36	4.35	3.36	3.36	4.84
5	4.31	4.31	4.31	3.32	3.32	4.35
6	4.28	4.28	2.38	1.39	0.63	4.38
7	2.64	2.64	2.64	1.65	1.65	4.22
8	2.55	2.55	2.55	1.56	1.56	4.28
9	2.45	2.45	2.45	1.46	1.46	3.96
10	2.37	2.37	2.37	1.38	1.38	3.56
11	2.37	2.37	2.37	1.38	1.38	2.42
12	2.24	2.24	2.24	1.25	1.25	2.26
13	2.00	2.00	2.00	1.01	1.01	2.10
14	1.75	1.75	1.75	1.75	1.75	1.94
15	1.50	1.50	1.50	1.50	1.50	1.77
16	1.37	1.37	1.37	1.37	1.37	1.61
17	1.21	1.21	1.17	1.17	1.21	1.22
18	1.21	1.21	1.17	1.17	1.21	1.22
19	1.21	1.21	1.17	1.17	1.21	1.22
20	1.21	0.22	1.18	0.19	0.22	1.23
21	1.22	0.23	1.18	0.19	0.23	1.23
22	1.25	0.26	1.48	0.49	0.20	2.11
23	1.86	0.87	0.61	0.61	0.53	2.60
24	2.05	1.06	0.73	0.73	0.63	3.09
25	2.42	1.43	0.97	0.97	0.83	3.58
26	2.54	3.29	2.52	2.52	2.13	3.70

27	2.50	2.89	2.52	2.52	2.18	3.86
28	3.49	2.50	2.61	2.61	2.01	3.98
29	3.78	2.79	2.91	2.91	2.26	4.40
30	4.17	3.18	3.19	3.19	2.51	4.85

3.2 Total annualized savings

Once obtained the consumption per trip for each layout and ambient temperature scenario, the hour frequency distribution was used to estimate the total yearly energy consumption and yearly energy savings through eq. 2 and 3.
The operational factors were estimated based on the trip schedule in winter and summer.

$$E_{con} = \dot{P}_{el} N_{hours} OP \cdot AF \qquad \text{Eq. 2}$$

With AF: 0.995.
OPsummer = 0.82
OPwinter : 0.91

$$E_{sav,year} = E_{year,R410a} - E_{year,R744+Li} \qquad \text{Eq. 3}$$

The energy consumption is depicted in the Figure 2.

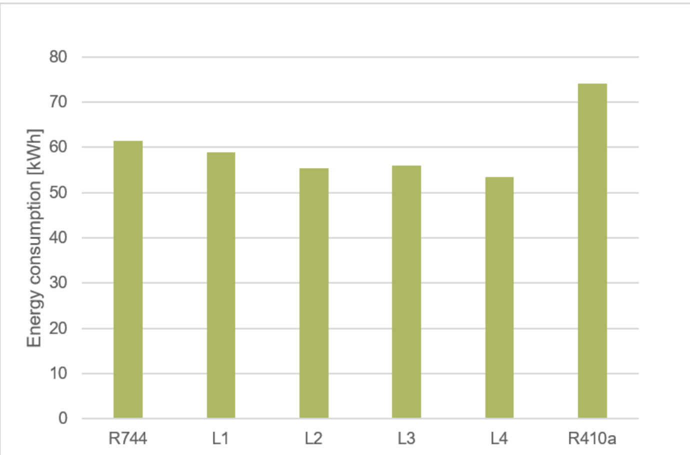


Figure 2. Comparative energy consumption of different BTM layouts and HP systems trough a year.

Table 3. Comparative energy savings for the different BTM layouts and R744 heat pump for each outdoor temperature

T_{out} [°C]	Energy savings [kWh]				
	R744	R744 + L1	R744 + L2	R744 + L3	R744 + L4
-5	21.41	59.29	52.00	59.29	52.00
-4	34.32	90.51	11.44	12.77	11.44
-3	50.94	242.45	16.98	53.23	16.98
-2	76.75	444.98	25.58	106.94	25.58
-1	56.82	598.74	18.94	137.80	18.94
0	17.27	408.22	5.76	115.28	5.76
1	104.15	578.74	34.72	163.83	34.72

2	206.80	366.59	68.93	84.83	68.93
3	415.61	563.05	138.54	142.03	138.54
4	497.50	497.50	165.83	165.83	165.83
5	52.89	52.89	17.63	17.63	17.63
6	136.89	136.89	885.08	885.08	1218.20
7	2212.89	2212.89	737.63	737.63	737.63
8	2551.93	2551.93	850.64	850.64	850.64
9	2352.83	2352.83	784.28	784.28	784.28
10	1854.41	1854.41	618.14	618.14	618.14
11	80.19	80.19	26.73	26.73	26.73
12	22.88	22.88	7.63	7.63	7.63
13	136.17	136.17	45.39	45.39	45.39
14	220.79	220.79	73.60	73.60	73.60
15	278.82	278.82	92.94	92.94	92.94
16	203.58	203.58	67.86	67.86	67.86
17	10.92	10.92	13.04	13.04	13.70
18	9.81	9.81	11.72	11.72	12.31
19	7.64	7.64	9.12	9.12	9.58
20	6.15	22.03	7.34	7.34	7.71
21	5.39	19.30	6.43	6.43	6.76
22	238.33	218.57	57.99	57.99	84.84
23	154.04	243.02	69.79	69.79	75.18
24	144.71	212.86	63.52	63.52	67.99
25	130.39	200.19	60.73	60.73	65.78
26	96.46	71.30	5.47	5.47	16.15
27	76.46	57.12	6.67	6.67	12.93
28	16.75	35.89	4.43	4.43	11.26
29	13.70	25.42	3.63	3.63	8.39
30	4.98	9.79	1.65	1.65	3.30
Total	**12501.58**	**15098.21**	**18727.02**	**18043.77**	**20486.93**

According to the calculations, the highest saving is achieved by the Layout 4, which accounts for a waste heat recovery system in combination with the Layout 2.

4. Thermoeconomical assessment

The thermoeconomical analysis was conducted under 10 years with a payback ratio of 5%. The Life Cycle assessment (LCC) defined the CAPEX and OPEX through the next equation:

$$LCC = CAPEX + \sum_{t=1}^{n} \frac{C_{energy} + C_{ref} + C_{maint}}{(1+r)^t} \quad \text{Eq. 4}$$

The energy price was estimated from the Full Evaluation Report and Energinet.dk https://www.energinet.dk/el/elmarkedet/tariffer/aktuelle-tariffer/. It was made a projection and averaged on 0.06 eur/kWh

The operational cost of the refrigerant and maintenance were estimated with the Equation 5 and 6.

$$C_{ref} = m_{ref}p_{ref} + m_{ref}p_{ref}f_{leak} + m_{ref}f_{leak}GWP\tau_{CO2e} + \sum_{t=1}^{n} \frac{m_{ref}p_{ref}f_{leak}}{(1+r)^t} \qquad \text{Eq. 5}$$

The operative cost of the refrigerant combines the initial fill of the refrigerant, whose mass was estimated from the manufacturer and the simulation [5], the operational annual leakage [6], an operational tax fee and leakage rate trough the projected time [7].

$$C_{maint} = \dot{Q}_{max,nom}p_{maint} \qquad \text{Eq. 6}$$

And the values are shown in the Table 4.

Table 4. Main parameters to estimate the operational costs regarding refrigerant and maintenance [8 – 9].

Parameter	R744	R410a
Refrigerant mass, m_{ref} [kg]	2.2	5.9
Leak rate, f_{leak}	0.15	0.15
Price/kg, p_{ref} [eur]	10.794	37.5
Payback ratio, *r*	0.05	0.05
GWP [$kgCO_{2eq}/kg_{ref}$]	1	2088
Environmental tax fee, τ_{CO2e} [eur/kgCO2e]	0	6.264
p_{maint} [eur]	18	35

The prices for the heat pumps, BTM components and auxiliaries were calculated based on manufacturers' information and correlations.

Table 5. BTM and HP layouts total prices including components, devices, piping, electrical, control, casing, and installation.

Component	Price [eur]
R410a HP	39600.00
R744 HP	49123.13
Layout 1 (additional finned-tube HX and piping)	60368.37
Layout 2 (additional plate HX and piping)	57334.64
Layout 3 (additional chiller-plate HX and piping)	60746.84
Layout 4	59224.33

A simple payback period (SPP) can be estimated in a straightforward way by the equation 6:

$$SPP = \frac{\Delta CAPEX}{\Delta OPEX} \qquad \text{Eq. 7}$$

Table 6. Estimation of a simple payback period of the different BTM layouts and HP systems.

System	R410a	R744	L1	L2	L3	L4
C_{energy} [eur]	1480.96	1230.93	1178.99	1106.42	1120.08	1071.22
C_{ref} [eur]	1126.64	27.37	61.58	61.58	27.37	27.37
C_{maint}[eur]	717.50	369.00	389.50	389.50	389.50	389.50
Total OPEX [eur]*	4881.88	12267.43	4890.21	4672.48	4610.85	4464.26
SPP [year]		1.87	4.08	3.34	3.94	3.56

*The total price includes the three units

But the LCC method is more accurate, having in account the payback ratio and projected to t = 10 years, by Equation 4. The results are in Table 7 and Figure 3.

Table 7. Estimation of the comparative LCC analysis of the different BTM layouts against the baseline HP and proposed R744 HP.

LCC [eur]						
t	R744	R410a	L1	L2	L3	L4
0	49,123.13	39,600.00	60,368.37	57,334.64	60,746.84	59,224.33
1	53,782.22	49,670.10	65,047.51	61,806.42	65,147.81	63,485.69
2	58,219.02	59,735.69	69,502.86	66,064.28	69,338.77	67,922.49
3	62,444.14	69,796.97	73,745.14	70,118.48	73,329.77	72,147.61
4	66,467.71	79,854.17	77,784.60	73,978.82	77,130.36	76,171.18
5	70,299.35	89,907.46	81,630.97	77,654.58	80,749.63	80,002.82
6	73,948.23	99,957.03	85,293.50	81,154.65	84,196.27	83,651.70
7	77,423.09	110,003.07	88,781.02	84,487.43	87,478.51	87,126.56
8	80,732.23	120,045.74	92,101.92	87,660.97	90,604.20	90,435.70
9	83,883.57	130,085.20	95,264.18	90,682.88	93,580.84	93,587.04
10	86,884.65	140,121.60	98,275.41	93,560.43	96,415.52	96,588.12

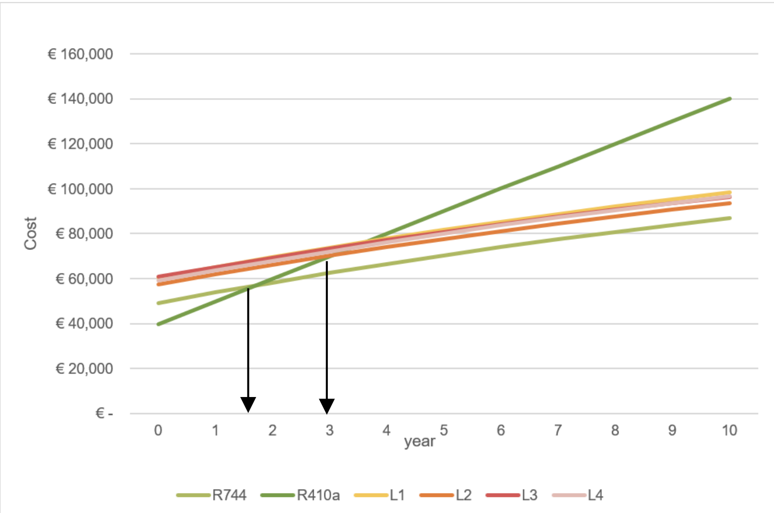


Figure 3. A payback period estimation based on the LCC.

Despite the initial investment, the LCC analysis identifies a crossover point where R744 configurations become more cost-effective. Given the substantial OPEX savings derived from reduced annual energy consumption, the system achieves payback and generates net positive value well within its 5-year operational lifecycle.

5. Environmental assessment integration

The Total Equivalent Warming Impact (TEWI) accounts for both direct refrigerant-specific GWP tax considerations and indirect energy-related emissions. It was estimated by Equation 8 [10-12].

$$TEWI = GWP\left(f_{leak} \cdot t + m_{ref}(1-\alpha)\right) + \left(E_{year} \cdot \beta \cdot t\right) \quad \text{Eq. 8}$$

Where t is the lifetime in years (10), E_{year} is the yearly total energy consumption in kW, α is the recycling factor and β the indirect emission factor. This calculation parameters are defined in the Table 7 and 8.

Table 8. Main parameters to estimate the TEWI.

Parameter	R744	R410a
Recycling factor, α	0.95	0.95
Indirect emission factor, β [kg CO_2/kWh]	0.17	0.17
Leak rate, f_{leak}	0.15	0.15

The first term of the equation 8 accounts for the direct TEWI and the second term are the indirect TEWI. The total TEWI comparative results can be seen in table 9 and Figure 4. The transition to R744 effectively eliminates the direct warming impact associated with high-GWP refrigerants like R410a.

Table 9. Comparison of total TEWI of different BTM layouts and HP systems.

TEWI [kg CO_2]	R410a	R744	L1	L2	L3	L4
Direct	5.1696	0.0016	0.0016	0.0016	0.0016	0.0016
Indirect	122.9934	102.2283	97.9153	91.8879	93.0227	88.9647
Total	128.16	102.23	97.92	91.89	93.02	88.97

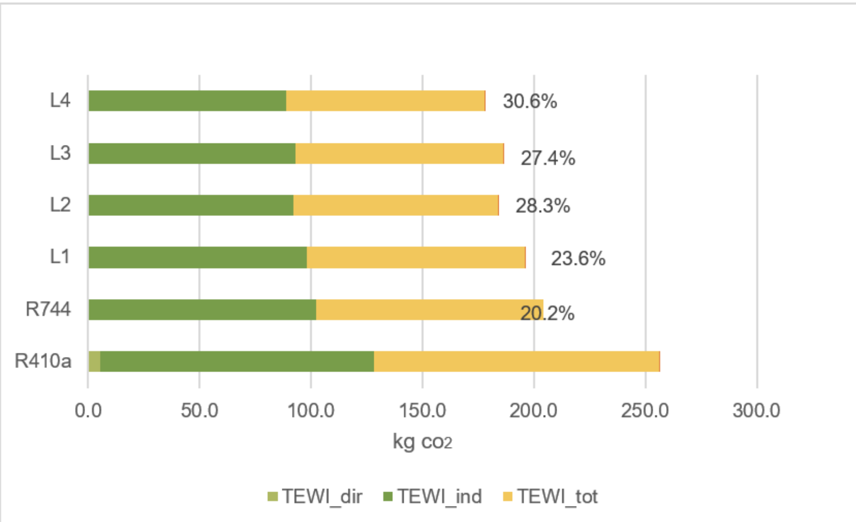


Figure 4. Comparative total equivalent warming impact, TEWI in kg CO_2. In light green the direct TEWI, mostly for the baseline R410a. In dark green the indirect TEWI and the total TEWI in yellow. The graph also shows the comparative savings of each system based on the baseline. The highest saving is in the L4 BTM which includes a waste heat recovery system.

6. Driving Range extension

To calculate the drive range extension (%DR), the energy saved by trip was converted in extended distance, through Equation 9 and the parameters in Table 1, using the monthly distribution ambient temperature.

$$\%DR = \frac{d_{ext}}{d_{trip}} = \frac{E_{trip} v_{nom}}{P_{prop} d_{trip}} \cdot 100\% \qquad \text{Eq. 9}$$

Where E_{trip} is the energy saved, and v_{nom}, P_{prop} and d_{trip} are in Table 1.

The results are depicted in Figure 5.

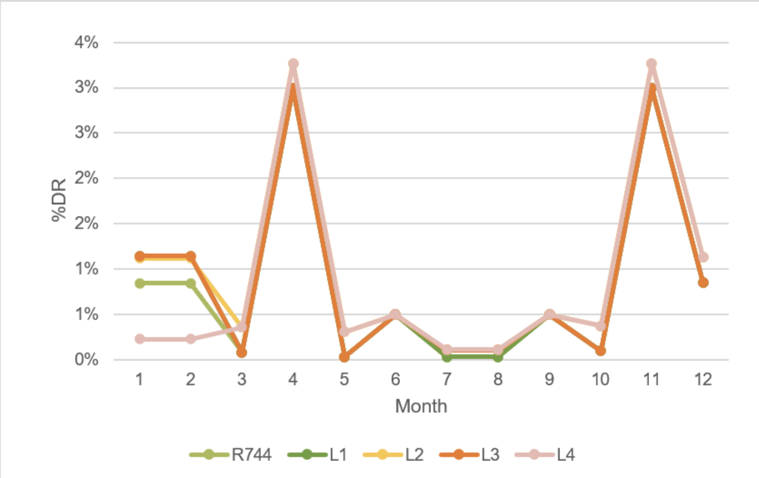


Figure 5. Drive range extension estimation. Comparison among different BTM layouts during a year.

The efficient management of thermal loads translates directly into propulsion range extension. Performance peaks in April and November because of the average outdoor temperature with higher energy savings (Table 3).

Limitations of the research and assumptions

- Lack of data about the behavior of the thermal storage system
- Lack of data of the curve load and control settings
- Assumption of steady state with a fixed outdoor temperature is not accurate. The real behavior is a dynamic outdoor temperature and a dynamic demand during a ferry trip, and during the day.
- Assumption of average electric consumption during a trip and extended to a day is not accurate due to the outdoor temperature dynamics.
- Assumption of electricity price. It was taken at a fixed price, which is unrealistic.
- Assumption of fixed service speed and propulsion power for the calculation of the extended drive range is not accurate.

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