SUPPORTING INFORMATION

CLOSING DATA GAPS FOR LCA OF FOOD PRODUCTS: ESTIMATING THE ENERGY DEMAND OF FOOD PROCESSING

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Methods

1. Physicochemical properties of foods. Physicochemical properties of the raw material are necessary to estimate the energy demand in those unit operations related to heat transfer. Table S1 provides an overview of data for some example products.

Table S1. Physicochemical properties for some example food products

Product	T (ºC)	Moisture content (% wet basis)	Apparent density (kg/m^3)	Freezing temperature (ºC)	Specific heat (kJ/kg ºC)	Latent heat kJ/kg
Wheat flour[1, 2, 3]	20 25.2-78.3	13.2 12-13.5 11.97	710 480		1.85>T_f 1.17>T_f 1.720	
Cocoa powder[1]	-	4.4	360			
Coffee (instant)[1, 3]		- 2.5	330 330			
Coffee (ground and roasted)		- 7	330 330			
Milk powder[1, 3]		2-4	610			
Salt (granulated)[1, 2, 3]	-	- 0.2 -	960 960		 1.130-1.339	
Sugar (granulated)[1, 2, 3]	 54.7-59.1	- 0.5 13.3	800 800		 1298-1256	
Sugar (powder)[1, 3]		 0.5	480 480			
Milk[3]		87.5		-0.6	3.89>T_f 2.05<T_f	288
Apple juice[1, 3]	-	87.2 87.2	1227 1051		 3.85	
Orange juice[1, 3]	80	89.2 89	1294	 -1.2	 3.89>T_f	
Apple[1, 2 ,3]	28 20-50	85.8 87.3 84	840	 -2	3.690 3.6>T_f 1.85>T_f	 280-282
Orange[1, 2, 3]	28 -	85.9 - 87.2	768	 -2.2	 3661 3.77>T_f 1.93<T_f	 288
Vegetable[4]					4.19	
Carrot[1, 2, 3]	28 27-66	90 88.2	1040	 -1.3	 2.272 3.7>T_f 1.85<T_f	 293
Cauliflower[1, 3]		91.7	320	-	3.89>T_f 1.97<T_f	307
Green bean[1, 3]		90.0	384	-1.8	3.94>T_f 2.39<T_f	297
Spinach[1, 3]		85-93	224	-1	3.94>T_f 2.01<T_f	307
Potato[1, 2, 3]	25 40-50	83.6 76.3-78.8 77.8	1040	 -1.7	 2.735-3.335 3.40>T_f 1.8<T_f	 258
Onion[1]	55	81.3	1229			
Green pea[1, 3]	60	75 74.3	1030	 -1.1	3.31>T_f 1.76<T_f	 247
Beef lean[1, 2, 3]	30	 72	1077	-2.2	3.431 2.51>T_f 1.47<T_f	 184
Pork boneless[1, 2, 3]	23	60-75	1090	-2	2.85 >T_f 1.6 < T_f	201
Pork (lean)[2]		57			3.054	
Poultry muscle[1, 2, 3]	23 -	72 -	1100		 3.530	

		74		-2.8	3.31> T_f 1.55 < T_f	247
Cod[1, 3]			1100	-2.2	3.770 > T_f 2.050 < T_f	277
Tuna[1, 2, 3]	20 10-95	72.3 70.8 70	1071	-	3.180-3.607 3.180> T_f 1.720 < T_f	-

These properties can also be calculated from composition data. The basis is to consider the food as being homogeneous but consisting of water (x_W), fat (x_F), carbohydrate (x_C), protein (x_P), and mineral fraction (x_M).

$$x_W + x_F + x_C + x_P + x_M = 1 \quad \text{(S1)}$$

The changes in thermal properties during freezing are dominated by the change in phase of the water component from liquid water to ice.[4] The aqueous component is modeled as a mixture of ice and a solution of the nonaqueous components in the liquid water which causes freezing point depression. Some of the water is loosely bound to the components (such as protein) and is never available to freeze. The total water component is thus modeled as consisting of three fractions - liquid water, ice, and bound water:

$$x_W = x_{LW} + x_I + x_B \quad \text{(S2)}$$

The fraction of ice can be calculated from Schwartzberg: [5]

$$x_I = (x_W - x_B)\left(1 - \frac{T_f}{T}\right) \quad \text{(S3)}$$

Where T is the food temperature and T_f is the freezing temperature of the food. The bound water fraction must be known to estimate x_I. It is commonly related to the solid mass fraction:

$$x_B = b x_S \quad \text{(S4)}$$

Some values of b can be found in the literature.[4] If data are not available then the use of b = 0.25 is suggested.

Density can be calculated as:

$$\frac{1}{\rho} = \sum_j \frac{x_j}{\rho_j} \quad \text{(S5)}$$

To estimate the specific heat (c), the most common approach is to sum up the contributions from the components. Above T_f, the model recommended is:

$$c = \sum_j x_j c_j \quad \text{(S6)}$$

Below T_f, effects due to phase change by the water fraction must be added. Schwartzberg[5] developed one of the simplest models assuming that component heat capacities are constant with temperature $c = c_u - (x_W - x_B)\left[\frac{L\prime T_f}{T^2} + (c_W - c_I)\right]$ (S7)

Where *L'* is the latent heat of freezing for water, *L'* = 334 kJ/kg.

The latent heat of freezing (*L*) results solely from the change in phase of water. L can be estimated from the latent heat of water and the ice fraction:

$L=x_I \cdot L'$ (S8)

The thermal conductivity can be calculated as a function of food volume fractions (v_j):

$k = \sum_j v_j k_j = \rho \sum_j \frac{x_j k_j}{\rho_j}$ (S9)

Below T_f the thermal conductivity of a food can be estimated from:[4]

$\frac{1}{k} = \frac{(v_{LW}+v_B)}{k_W} + \frac{(1-v_{LW}-v_B)^2}{\sum_{j\ not\ LW,B} v_j k_j}$ (S10)

The thermal diffusivity can be calculated as:

$\alpha = \frac{k\rho}{c}$ (S11)

The above equations require data for the thermal properties of the components. Although these properties do change with temperature, for the sake of simplicity average values are commonly used. Table S2 states typically used average values for the components of interest.

Table S2. Properties of pure components[4]

	ρ_i (kg/m^3)	c_i J/kg K	k_i W/m K
LW, B (liquid water, bound water)	1000	4180	0.56
I (ice)	917	2110	2.22
F (fat)	930	1900	0.18
S (solids)	1450	1600	0.22
P (protein)	1380	1900	0.2
C (carbohydrates)	1550	1500	0.245
M (mineral)	2165	1100	0.26

2. Input data

Tables S3 and S4 show some data from published literature on energy consumption of unit operations.

Table S3. Energy consumption of unit operations for food processing.

Unit process	Product	Thermal energy (MJ/kg product)	Electricity (MJ/kg product)	Data origin
Steam peeler[6]	-	0.29	3.42E-03	
Steam blancher with no end seals	Spinach[7]	2.12	4.24E-02	Measured in plant
Steam blancher hydrostatic		0.95	1.90E-02	
Steam blancher hydrostatic/ventury		0.91	1.82E-02	
Steam blancher water curtains	Grean beans[7]	1.56	3.12E-02	
Screw conveyor blancher	Cauliflower[8]	0.91		Measured in plant
Tubular water blancher	Lima beans[8]	0.54	1.10%	
Integrated blancher-cooler	Peas[9]	0.21-0.48	3.8E-3 – 1.04E-2	
Receiving	Spinach canning[10]		2.78E-03	Measured in plant
Dry reel cleaning			3.59E-03	
Washing			4.38E-02	
Blanching		1.48	4.64E-03	
Sorting			7.26E-04	
Filling			6.60E-03	
Exhaust box		2.11	3.45E-03	
Seaming			1.01E-02	
Retorting (sterilization)		0.67	5.48E-05	
Palletizing		-	1.85E-03	
receiving station	Tomato juice[11]		1.05E-03	Measured in plant
Sorter			1.03E-04	
Crusher			1.39E-03	
Pump			6.69E-04	
Hot break		2.37E-01	3.86E-04	
Pump			8.74E-04	
Pulper			2.43E-03	
Finisher			4.80E-04	
Pump			1.37E-04	
Screw press & conveyors			5.78E-05	
Filler/seamer			5.99E-04	
Retort		4.39E-01	1.18E-03	
Receiving station	Peeled tomato canning[12]		1.05E-03	Measured in plant
Size grader			4.03E-05	
Roller/washer			1.18E-04	
Recirculation pump			9.08E-05	
Elevator			2.44E-05	
Lye-Bath		2.12E-01	7.05E-04	

Conveyor			1.39E-05	
Rubber-disc peeler			4.73E-04	
Elevator/conveyor			2.62E-05	
Sorter			3.93E-05	
Slicer			1.41E-04	
Conveyor			2.98E-05	
Filler			1.30E-03	
Retort		9.58E-01	1.81E-03	
Other processes	Peeled tomato canning[6]		0.013	
Peeling with alkaline solution			0.234	
Sterilizing		1.053		
Receiving station	Concentrated tomato[12]		1.05E-03	Measured in plant
Sorter			7.83E-05	
Crusher			1.06E-03	
Pump			5.09E-04	
Heat Exchanger (horizontal)		1.69E-02		
Heat Exchanger (vertical)		2.32E-01		
Pulper			1.67E-03	
Finisher			3.35E-04	
Pump			8.35E-05	
Pump			4.18E-05	
Evaporator		9.85E-01	1.10E-04	
Pump			7.04E-05	
Pump			4.67E-05	
Swept surface finisher (Rotovac)		2.47E-01	6.78E-04	
Pump			2.94E-05	
Pump			7.83E-05	
Tomato concentration 5-30ºBrix 1 effect	Tomato concentration[11]	2.01E+00	2.70E-02	
Tomato concentration 5-30ºBrix 2 effects		1.21E+00	2.82E-02	
Tomato concentration 5-30ºBrix 3 effects		9.18E-01	2.23E-02	
Tomato concentration 5-30ºBrix 4 effects		7.65E-01	1.41E-02	
Apple juice concentration 12-72ºBrix 2 effects	Apple juice concentration[11]	3.00E-01	6.90E-01	
Apple juice concentration 12-72ºBrix 3 effects		1.70E-01	3.00E-01	
Apple juice concentration 12-72ºBrix 4 effects		1.60E-01	3.00E-01	
Washing, squeezing, centrifugation	Orange juice concentration[13]	2.86E+00		Literature data
Concentration		6.44E-01		
Pasteurization, low energy pulsed electric field		2.592		
Dilution				
Washing, squeezing, centrifugate	Direct orange juice[13]	2.69E+00		Literature data
Pasteurization, low energy pulsed electric field		2.592		
Thawing	Canned tuna, from frozen raw tuna[14]	1.11E-1	2.41E-3	Measured in plant
Cutting			8.50E-2	

Cooking		1.39E+00	8.71E-2	
Manual cleaning of tuna			3.49E-2	
Liquid dosage and filling			1.70E-1	
Sterilization		1.94E+00	1.64E-1	
Packaging			1.20E-1	
Cutting, filling	Raw sausage[6]		3.6	
4 weeks ripening in controlled climate			32.4	
Solvent extraction process Extraction: pretreatment	Rapeseed -or sunflower oil[6]	0.075-0.095 vapor / kg seed	0.09-0.126 MJ / kg seed	
	Soybean oil[6]	0.1-0.12 vapor / kg seed	0.054 MJ / kg seed	
Extraction: press, extraction	Soybean oil[6]	0.25 kg vapor / kg seed	0.0432 MJ / kg seed	
Extraction: separation	Vegetable oil[6]	-	-	
Extraction: treatment of press cake		-	-	
Refining: neutralizing		-	-	
Refining: saponification		0.085-0.15 kg vapor	0.0144 – 0.0468	
Refining: bleaching		-	-	
Refining: deodorization		0.1-0.3 kg vapor	0.0072	
Reception	UHT milk[15]		0.89	
Pasteurization		2.844	8.9	
Sterilization		3.95	11.57	
Packaging			12.015	
Anc. activities (CIP + compressed air)		0.711	10.235	
Steam blanching	Vegetable[6]	9		calculated
Grinding seed to flower	Wheatflower[6]		0.223	
	Ryeflower[6]		0.266	
Wet grinding and drying	Corn starch[6]		5.676-7.2	
Rice milling (raw material to ready to eat rice)	Rice[6]		0.27	
Mixing , dispersing, forming, predrying and drying (if 100 kg / h)	Pasta[6]	0.73	0.342-0.45	
Production of bakery products	Toast bread wheat[6]	5.94	1.98	
	Wheat-rye-bread[6]	11.34	3.78	
	Crisp bread[6]	44.82	14.94	
	Small wheat bakeries[6]	10.26	3.42	
	Yeast semi-sweet bakeries[6]	5.94	1.98	
	Pretzel[6]	17.82	5.94	
	Cracker[6]	10.8	3.6	
	Cookies, gingerbread[6]	7.56	2.52	
	Biscuit, cake[6]	6.48	2.16	
	Extruded bread/crouton cutter[6]	2.7	0.9	
Potato processing	Dried potatoes[6]	17-22	1.08-2.16	
	Potato flakes[6]	17-22	0.36-1.08	

	Potato granulate[6]	22-33.5	1.8-2.16	
	French fries[6]	25-33.5	7.2-10.8	
Production (if 2000 l/h)	Soymilk[6]	0.285	0.144	
Cooling during production process			0.175	
Production	Sugar from sugar beet[6]	7-7.5	0.828	
Cleaning, cutting, fermentation, blanching, packaging, pasteurizing (yield 70 %)	Sauerkraut[6]		1.154	
Cleaning, sorting, packaging, pasteurizing (yield 95 %)	Gherkin[6]		0.227	
Cleaning, drying, storage, soaking, germination, kiln drying, cleaning	Malt[6]	1.4-4	0.288-0.432	
Production (raw material = malt…)	Beer[6]		0.165-0.21	
Fermentation	Vinegar[6]		0.126-0.135	
Fetter procedure	Vinegar[6]		0.036	
Conventional production without pretreatment	Chocolate[6]		0.846-0.936	
Conventional production with pretreatment of the cacao			0.486-0.54	
Petzholdt-procedure (PIV) without pretreatment			0.306-0.36	
Petzholdt-procedure (PIV) with pretreatment			0.288-0.306	
Konticonche (depending on the recipe)			0.18-0.288	
Thouet-Conche at chocolate coating			0.162-0.234	
Thouet-Conche at chocolate			0.306-0.648	
Production (molasses, water to yeast)	Yeast fresh[6]	0.43	1.026	
Production (molasses, water to yeast)	Yeast dried[6]	2.95	7.164	
A lot of "detailed" information available	Coffee[6]			
Vacuum method (4 steps)	Salt from brine[6]	2.5	0.0612	
Thermo-compression	Salt from brine[6]	0.28	0.468-0.54	

Table S4. Energy consumption of some process units in dairies[16]

	Steam MJ/kg skim milk	Power MJ/kg skim milk	Fuel Oil MJ/kg skim milk
5 effect evaporator + TVR, 8.5 to 48% solids	0.216	0.018	
7 effect evaporator + TVR, 8.5 to 48% solids	0.160	0.018	
1 effect evaporator + MVR /2 effect evaporator + TVR, 8.5 to 48% solids	0.05	0.048	
Spray Dry + Pneum, 48 to 96.5% solids	0.000	0.189	3.294
Spray Dry + VibroF, 48 to 96.5% solids	0.131	0.183	2.637
Spray Dry HT + VibroF, 48 to 96.5% solids	0.132	0.159	2.517
Spray Dry Ring Fluid Bed, 48 to 96.5% solids	0.189	0.140	2.079
Spray Dry Circulated Static Fluid Bed, 48 to 96.5% solids	0.200	0.120	1.789

3. Blanching. Convection heat losses (Q_{conv}) in a blancher can be calculated as:

$$Q_{conv} = A\ h\ (T_s - T_a) \quad \text{(S12)}$$

Where *A* is the external surface of the blancher (m^2); *h* is the heat transfer coefficient ($kJ/m^2\ ^oC$); and *Ts* and *Ta* are the temperature (^oC) of the blancher surface and the surrounding air, respectively.

The radiation losses (Q_{rad}) can be calculated from:

$$Q_{rad} = \varepsilon\ \sigma\ A\ (T_s^4 - T_w^4) \quad \text{(S13)}$$

Where ε is the emissivity of the material of the blancher surface; *s* is the Stefan-Boltzman coefficient ($5.669 \cdot 10^{-8}$ W/m^2 K); and T_w is the temperature of the surface that surrounds the blancher.

4. Evaporation. Figure S1 shows a schematic diagram of a typical single-effect evaporator showing energy and material flows.

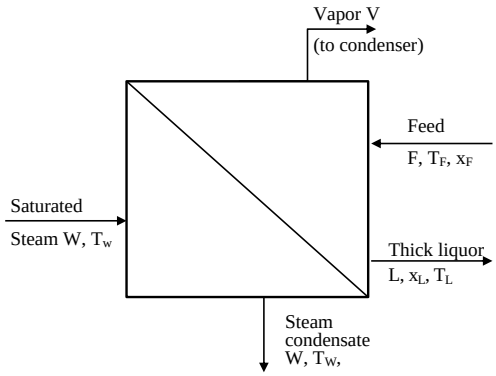

Figure S1. Representation of a single effect evaporator

In order to calculate the energy consumption of a single stage evaporator first we need to know the amount of vapor released from the food that can be calculated from the total mass (eq S14) and solute balance (eq S4):

$$F = L + V \quad \text{(S14)}$$

$$FX_F = LX_L \quad \text{(S15)}$$

Where F is the flow of feed (kg/s) that is known; L is that of the concentrate (thick liquor); x_F and x_L are the mass fractions of solids in the feed and concentrate streams, respectively, that are data also known; and V is the rate of vapor flow.

The steam flow (W, kg/s) can be calculated from the energy balance, as follows:

$$W l_w = F\, c_F\, (T_b - T_F) + Vl \qquad \text{(S16)}$$

Where l_w (MJ/kg) is the latent heat of the steam at T_w, its condensing temperature; T_b the boiling temperature of the liquid in the evaporator; T_F the temperature of the feed; c_F the specific heat of the feed (MJ/^{0}C/kg) and l (MJ/kg) the latent heat of the vapor at T_b.

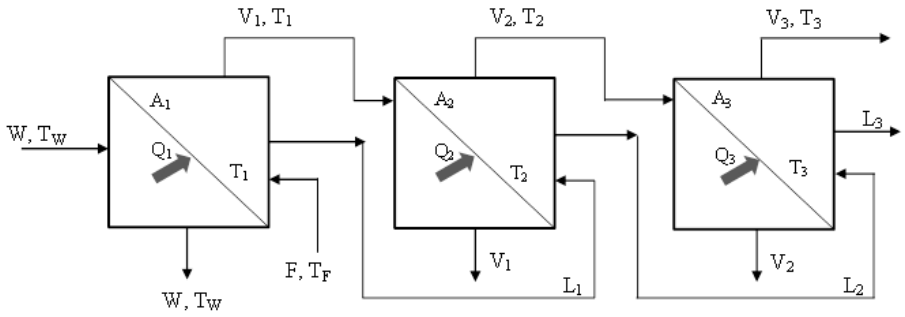

Figure S2. Representation of a three effect evaporator, direct circulation.

Figure S2 sketches a multiple evaporator with three effects and direct circulation. To calculate the steam flow for a multistage evaporator, besides the mass and the energy balances in each effect, two assumptions are made. The first one is that the area of the three stages is the same (supposing a three stages evaporator):

$$A_1 = A_2 = A_3 \qquad \text{(S17)}$$

The second assumption (eq S7) means that the heat transfer rate is the same in all the effects:

$$Q_1 = Q_2 = Q_3 \qquad \text{(S18)}$$

$$U_1\, A_1 \Delta T_1 = U_2\, A_2 \Delta T_2 = U_3\, A_3 \Delta T_3 \qquad \text{(S19)}$$

$$\frac{\Delta T_1}{U_1} = \frac{\Delta T_2}{U_2} = \frac{\Delta T_3}{U_3} = \frac{T_w - T_3}{U_1 + U_2 + U_3} \qquad \text{(S20)}$$

From the last equation (eq S20), the temperature differences in each evaporator stage can be computed. These ΔT are needed for the energy balances, and from the energy balances the steam flow can be computed and from it the exchange area in each stage. In case that the

computed areas (A_1, A_2, A_3) are not the same (or differ more than 5% from the average area), a new approximation of the temperature difference in an effect i ($\Delta T'_i$) is obtained from the equation S21:

$$\Delta T'_i = \frac{\Delta T_i \cdot A_i}{A_{mean}} \quad \text{(S21)}$$

The energy balances are calculated again with the new ΔT and the calculation is repeated until the areas of each effect are sufficiently close together, that is, they differ less than 5% from the average area.

Values of *A* and *E* for different evaporator configurations are presented in Table S4.

Table S5. *A* and E (economy) coefficient values for several evaporator configurations.

Evaporator characteristics	Product	*A*	*E*
1-effect under vacuum[17]			0.75-0.95
6-effect under vacuum[17]			4.5-5.7
TASTE[18]	Orange juice	0.85	
5-effect 8-stages TASTE[19]	Orange juice	0.74	
Atmospheric evaporator with thermal energy recycling[20]			2.83
Single effect vacuum evaporator[21]			0.91
2- and 3-effects[11]	Tomato paste		1.38-2.60
1- to 3-effects vacuum with MVR[22]			1.67-3.33
5-effects with TVR[16]	Skim milk concentration from 9% to 50% solids		7.6
7-effects with TVR[16]			10.3
1- effect with MVR or 2-effects with TVR[16]			32.8

5. Dehydration. Figure S3 shows a simplified representation of a drying process.

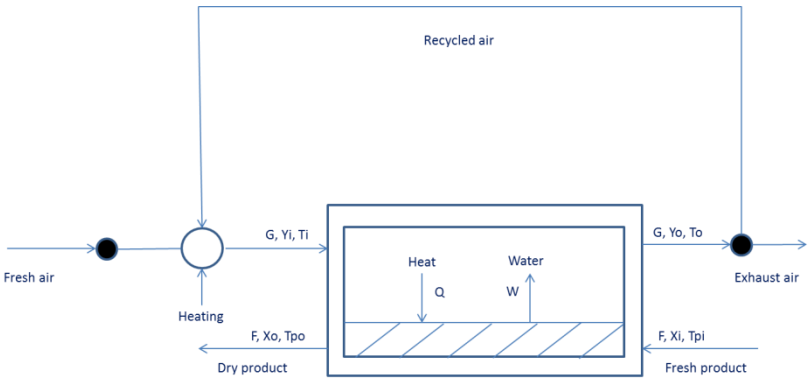

Figure S3. Representation of a dryer with air recycling.

Based on Figure S3 the mass and energy balances in a dryer are shown. Food related variables are mass flow rate F (kg dry solid/s) and water content X (kg water/kg dry solid), while drying air variables are mass flow rate G (kg dry air/s) and moisture content Y (kg vapor/kg dry air). Neglecting solid losses and leakages of air, both F and G remain constant throughout the drying process. The overall moisture balance gives the total amount of water transferred from the foodstuff to the air (W):

$$W = F\ (X_i - X_o) = G(Y_o - Y_i) \quad \text{(S22)}$$

where subscripts i and o indicate inlet and outlet, respectively.

The energy balance yields:

$$GH_{Go} + FH_{Fi} = GH_{Gi} + FH_{Fo} + q \quad \text{(S23)}$$

where q are the heat losses, and H_G and H_F the enthalpies of air and product, respectively:

$$H_G = c_G(T_G - T_R) + YH_L \quad \text{(S24)}$$

c_G is the humid heat of the air (kJ/kg dry air ºC), c_G = 1.005 +1.88Y; T_G is the air temperature at the outlet or inlet, depending on the case; T_R is the reference temperature; and H_L is the vaporization heat of water (kJ/kg water).

$$H_F = c_F(T_F - T_R) + Xc_w(T_F - T_0) \quad \text{(S25)}$$

where c_F is the specific heat of the product (kJ/kg ºC); T_F the product temperature at the inlet or outlet; and c_W the specific heat of water.

Table S6. Principal types of dryers in the food industry[23]

Dryer type	Operation	State of feed	Movement of bulk	Product examples
Cabinet	B	S	0	Fruit, vegetables, meat, fish
Tunnel	C	S	0	Fruit, vegetables
Belt	C	S, P	0	Fruit, vegetables, tomato
Belt-through	C	S	M	Vegetables
Rotary	C	S	M	Animal feed, waste
Bin	B	S	0	Vegetables
Grain dryers	B, C	S	0, M	Grain
Spray	C	S, P	M	Milk, coffee, tea
Fluid bed	B, C	S	F	Vegetables, grain, yeast
Pneumatic	C	S	M	Flour
Drum	C	L, P	0	Mashed potato, soup
Screw conveyor	C	S, P	M	Grain, waste
Mixer	B,	S	M	Particles, powders
Solar	B, C	All	All	All
Sun drying	B	S	0	Fruit, vegetables, fish
B = batch, C= continuous; S = solid, L = liquid, P = paste; 0 = static, M = moving, F= fluidized				

Table S7. Energy efficiency and thermal energy efficiency of selected industrial dryers[24]

Method or dryer type	Energy or thermal efficiency
Tray, batch	85
Tunnel	35-40
Spray	50
Tower	20-40
Flash	50-75
Conveyor	40-60
Fluidized bed, standard	40-80
Vibrated fluidized bed	56-80
Pulsed fluidized bed	65-80
Sheeting	50-90
Drum, indirect heating	85
Rotary, indirect heating	75-90
Rotary, direct heating	40-70
Cylinder dryer	90-92
Vacuum rotary	up to 70
Infrared	30-60
Dielectric	60
Freeze	around 10

Table S8. Energy consumption for selected dryers[25]

Dryer type	Typical energy consumption (kJ/kg of water evaporated)
Tunnel dryer	5500 - 6000
Band dryer	4000 - 6000
Impingement dryer	5000 - 7000
Rotary dryer	4600 - 9200
Fluid bed dryer	4000 - 6000
Flash dryer	4500 - 9000
Spray dryer	4500 - 11500
Drum dryer	3200 - 6500

Note from authors: figures are only approximate and based on current practice. Better results can often be obtained by optimizing operating conditions and using advanced technology to modify the earlier designs[24].

Table S9. Typical energy consumption and heat losses for industrial dryers[26]

Dryer type	Typical main heat loss sources	Typical energy consumption (MJ/kg evaporated water)
Rotary		
Indirect rotary	Surface	3.0-8.0
Cascade rotary	Exhaust, leaks	3.5-12.0
Band tray and tunnel		
Cross-circulated tray/oven/band	Exhaust, surface	8.0-16.0
Cross-circulated shelf/tunnel	Exhaust, surface	6.0-16.0
Through-circulated tray/band	Exhaust	5.0-12.0
Vacuum tray/band/plate	Surface	3.5-8.0
Drum	Surface	3.0-12.0
Fluidized/spouted bed	Exhaust	3.5-8.0
Spray		
Pneumatic conveying/spray	Exhaust	3.5-8.0
Two-stage	Exhaust, surface	3.3-6.0
Cylinder	Surface	3.5-10.0

6. Freezing. Freezing time can be calculated by using eq 11, shown in the main text. Table S10 shows the values of the constants for eq 11.

Table S10. Values of constants for eq 11[4]

Geometry	***m***	***n***	***c***	A_1	***B***
Slab[a]	1.04	0.09	0.18	-1.08125	62.9375
Slab[b]	1.03	0.10	0.16	-0.94250	62.4350
Infinite cylinder	1.00	0.09	0.17	-0.46875	28.7625
Sphere	0.90	0.06	0.18	-0.16875	15.3625

[a]Heat transfer perpendicular to fibres
[b]Heat transfer parallel to fibres

Typical contributions of the heat load components are given in Table S11. Once calculated the product heat load (Q_{pr}), the total heat load (Q_{tot}), and the energy consumption of the rest of components can be estimated from the percentages shown in the table.

Table S11. Typical component heat load percentages for well-designed freezers[4]

Freezer type	Product	Fans/pumps	Pull-down	Defrost	Other
Batch air-blast	50-80%	10-40%	<10%	<5%	<5%
Continuous air-blast	50-80%	10-40%	0%	10-20%	5-10%
Plate	85-90%	5-10%	<5%	<5%	<5%
Cryogenic	85-90%	<10%	<5%	0%	<10%

7. Refrigerated/frozen storage. The refrigeration requirement (or refrigeration load) of storage rooms comprise several terms: heat transfer through the insulation; air changes; introduction of goods at temperatures higher than that of the room; heat generated by respiration (fruits and vegetables); defrosting cycles; energy spent by fans, forklifts, conveyors, lighting, etc.; and people working in the room. In the following the equations to calculate each one of these terms are shown.

The heat transfer transmitted through the insulation ($Q_{transmission}$, kJ/day) is due to a temperature gradient between the outside and the inside of the chamber. This heat flow can be calculated as:

$$Q_{transmission} = U\ A\ (T_{out} - T_{in}) \quad \text{(S26)}$$

Where U is the global heat transfer coefficient (W/m^{2}K); A is the chamber surface; and T_{out} and T_{in} are the temperatures outside and inside (ºC).

The global heat transfer coefficient is calculated as:

$$\frac{1}{U} = \frac{1}{h_{out}} + \sum \frac{e_j}{k_j} + \frac{1}{h_{in}} \quad \text{(S27)}$$

Where h_{out} and h_{in} are the external and internal heat transfer coefficients (W m^{-2} K^{-1}); k_j is the thermal conductivity of each material of the insulating panel (W m^{-1} K^{-1}) and e_j is the thickness

of each material of the insulating panel. In insulated walls the external and internal thermal resistances, $1/h_{out}$ and $1/h_{in}$, can be neglected since they are very low compared with the other resistances.

With respect to the factor ($T_{out} - T_{in}$), T_{in} is the conservation temperature inside the chamber. Nevertheless for the external temperature T_{out} it's important to take into account some factors to avoid oversizing the cooling equipment. A possibility is to calculate T_{out} as:

$$T_{out} = 0.6\, T_{max} + 0.4\, T_{mean} \quad \text{(S28)}$$

T_{max} and T_{mean} are the highest and average temperature of the hottest month, respectively.

The air inside the chamber must be renewed periodically due to physiologic activity of the product. The heat transfer due to air changes (Q_{air}, kJ/day) is computed as:

$$Q_{air} = V\, \rho\, c_{air}\, (T_{air} - T_{in})\, N \quad \text{(S29)}$$

Where V is the volume of the chamber (m^3); ρ is the air density (kg m^{-3}); c_{air} is the specific heat of the air (kJ/kg K); and N is the number of air changes per day.

The heat due to the introduction of products ($Q_{product}$, kJ/day) at temperatures higher than that of the rooms calculated as:

$$Q_{product} = M\, c_{product}\, (T_{product} - T_{in}) \quad \text{(S30)}$$

M is the mass of product introduced, including packaging, (kg day^{-1}); $c_{product}$ is its specific heat (kJ kg^{-1} K^{-1}); $T_{product}$ is the temperature of the goods as they are brought into the chamber (ºC).

When computing the refrigeration load of fruits and vegetables, it has to be taken into account that this kind of products still has vital functions, mainly respiration. Thus the heat generated by respiration (Q_{resp}) can be computed as:

$$Q_{resp} = m\, q_r \quad \text{(S31)}$$

Where m is the mass of fruit or vegetable (kg); q_r is the respiration heat (kJ/kg day). The respiration heat can be obtained from tables such as ASHRAE[27].

The energy spent by fans, conveyors and lighting (Q_{others}) can be computed by using the following equation:

$$Q_{others} = 3600(P\, t + P' t') \quad \text{(S32)}$$

P is the sum of the power of the motors of fans, conveyors, etc. (kW); t is the working time of the motors (hours/day); *P'* is power of lighting system (kW); *t'* is the working time of the lighting system (hours/day). People working in the storage chamber supposes an energy entry as sensible heat (people temperature is higher than the one in the chamber) and as latent heat (due to people respiration). Thus this heat can be calculated as:

$$Q_{people} = n\ t\ q_p \quad \text{(S33)}$$

Being *n* the number of persons working in the storage room; *t* the time they are working inside (h day^{-1}); q_p is the average estimated respiration heat of one person (627 kJ/h).

In spite of the breakdown of the heat load presented above, there are always other aspects that have not been included such as defrosting, heat from the forklifts engines, enthalpies of water condensation and solidification on the evaporator. In a simplified way, this heat together with Q_{others} and Q_{people} can be jointly estimated as 20% of Q_i.

Table S12. Contribution of kinds of thermal energy loads to total thermal energy load and total electric consumption[28]

Kind of heat load	% of heat load	% of total electric consumption
Transmission ($Q_{transmission}$)	36	19
Infiltration (doors opening)	0	0
Product ($Q_{product}$)	14	7
Electric appliances (Q_{others})	50	74

7. Pasteurization

Table S13. Examples of heat treatment combination used in food pasteurization[22]

Food	Main goal	Secondary goal	Treatment conditions
Fruit juice (pH< 4.5)	Enzyme inactivation (pectinesterase, polygalacturonase)	Destruction of microorganisms causing food degradation	65ºC – 30 min 77ºC – 1 min 88ºC – 15 s
Beer (pH< 4.5)	Microorganism destruction (wild yeasts, lactobacillus and residual yeasts)		65-68ºC 20 min (bottles) 72-75ºC 1-4 min 900-1000kPa
Milk (pH>4.5)	Patogen destruction (Brucella abortis, Mycobacterium tuberculosis)	Destruction of enzymes and microorganisms causing food degradation	63ºC – 30 min 71,5ºC – 15 s
Liquid egg (pH>4.5)	Patogen destruction (Salmonella)	Destruction of microorganisms causing food degradation	64,4ºC – 2,5 min 60ºC – 3,5 min
Ice cream (pH>4.5)	Patogen destruction	Destruction of microorganisms causing food degradation	65ºC – 30 min 71ºC – 10 min 80ºC – 20 s

8. Baking/roasting

Table S14. Comparison of specific energy consumption in baking operation (adapted from[24]).

Type of baking	Specific energy consumption (MJ/kg)
General[22]	0.45-0.6
Bread (35000 kg/day)[29]	7.26
Bread (three bakeries)[30]	6.99
Bread, bakery size:[31]	
250000 kg/year (batch)	13.96
3500000 kg/year (continuous)	4.88
Bread (multizone oven in USA):[32]	
1700 kg/h	0.86
Bread (12 bakeries in Finland):[33]	
1000000 breads/year	6.5
Bread:[34]	
USA: 35000 breads/day	7.26
India 14040 kg/day	31.82
Bread:[35]	
9 ovens – gas fired	6.17
14 ovens - electricity	5.34

9. Pumping. The theoretical energy needed to pump a liquid through a pipe from point 1 to point 2 is calculated from the Bernoulli equation as pump head (ΔH_{pump} in meters) by means of the following equation:

$$\Delta H_{pump} = (z_2 - z_1) + \left(\frac{v_2^2 - v_1^2}{2g}\right) + \left(\frac{P_2 - P_1}{\rho g}\right) + \Delta H_{friction} \quad \text{(S34)}$$

Where z is the relative height (m), v is the velocity (m/s), P is the pressure (Pa), $\Delta H_{friction}$ is the pressure drop due to friction (m) and ρ is the density of the fluid (kg/m^3). The relationship between $\Delta H_{friction}$ and the Reynolds number (*Re*) is usually presented as log plots known as friction-factor charts. However, for laminar flow $\Delta H_{friction}$ can be computed as:

$$\Delta H_{friction} = \frac{64}{Re} \quad \text{(S35)}$$

And for turbulent flow:

$$\Delta H_{friction} = \frac{2\Delta P D}{L v^2 \rho} \quad \text{(S36)}$$

Where: *Re* is the Reynolds number, ΔP is the pressure drop (Pa), D is the diameter of the pipe (m), L is the length of the channel (m) and v is the average velocity of the fluid (m/s).

If we want to know the theoretical power needed from length units (m) as Jules:

$$W_{pump} = \Delta H_{pump} \cdot Q \quad \text{(S37)}$$

where Q is the volumetric flow rate (m^3·s^{-1}).

The actual energy consumption of the pump (W*)* is calculated from its mechanical efficiency (η_m):

$$\eta_m = \frac{W_{pump}}{W} \quad \text{(S38)}$$

10. Case Study

From the composition of spinach and using the equations presented above in section 1 of this SI, spinach physicochemical properties were estimated in Table S15.

Table S15. Physicochemical properties of spinach

Property	Value	Source
Density ρ	951.08 kg/m^3	eq S5
Specific heat unfrozen food c_u	4793.9 J/kg K	eq S6
Specific heat frozen food c_f	2206.9 J/kg K	eq S7
Thermal conductivity unfrozen food k_u	0.499 W/m K	eq S9
Thermal conductivity frozen food k_f	0.561 W/m K	eq S10
Latent heat of freezing L	$2.827 \cdot 10^5$ J/kg	eq S8
Thermal diffusivity α	$1.095 \cdot 10^{-07}$	eq S11

Table S16. Input parameters and estimated energy consumption for the case study on frozen spinach

Unit operation	Parameter	Value	Energy consumption (MJ/kg)			Equation Source
			average	minimum	maximum	
Selection and cutting	P_N (kW)	0.92 - 1.1	$1.02 \cdot 10^{-3}$	$9.27 \cdot 10^{-4}$	$1.11 \cdot 10^{-3}$	eq. 23 (36)
Washing	P_N (kW)	12 - 14	$1.31 \cdot 10^{-2}$	$1.21 \cdot 10^{-2}$	$1.41 \cdot 10^{-2}$	eq. 23 (36)
Centrifuge	P_N (kW)	1.1	$1.11 \cdot 10^{-3}$			eq. 2 (36)
Blanching	Steam		1.38	0.88	1.88	(37)
Packaging*	LDPE (g/kg spinach)	10.5	n.a.			Measured
	R (m) Half thickness	0.02				Measured
Freezing in a blast freezer	t_f (h) Freezing time	11.5				eq. 9
	Q_{pr}		$4.10 \cdot 10^{-1}$			eq 11
	Q_{fan}		$1.58 \cdot 10^{-1}$	$5.13 \cdot 10^{-2}$	$3.28 \cdot 10^{-1}$	percentages from Table S10
	Q_{comp}		$3.82 \cdot 10^{-1}$	$3.11 \cdot 10^{-1}$	$4.97 \cdot 10^{-1}$	eq 12 assuming COP 1.65
	Q_{anc}	15-20% Q_{comp}	$6.69 \cdot 10^{-2}$	$4.66 \cdot 10^{-2}$	$9.94 \cdot 10^{-2}$	
	$Q_{fan}+Q_{comp}+Q_{anc}$ Total electricity		$6.07 \cdot 10^{-1}$	$4.09 \cdot 10^{-1}$	$9.25 \cdot 10^{-1}$	
Frozen storage 365 days	Electricity		$8.90 \cdot 10^{-01}$			(38)

*Due to lack of data the energy consumption of this operation was not calculated

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