Assessment of the scope of tasks to completely phase out fossil fuels in Hawai‘i

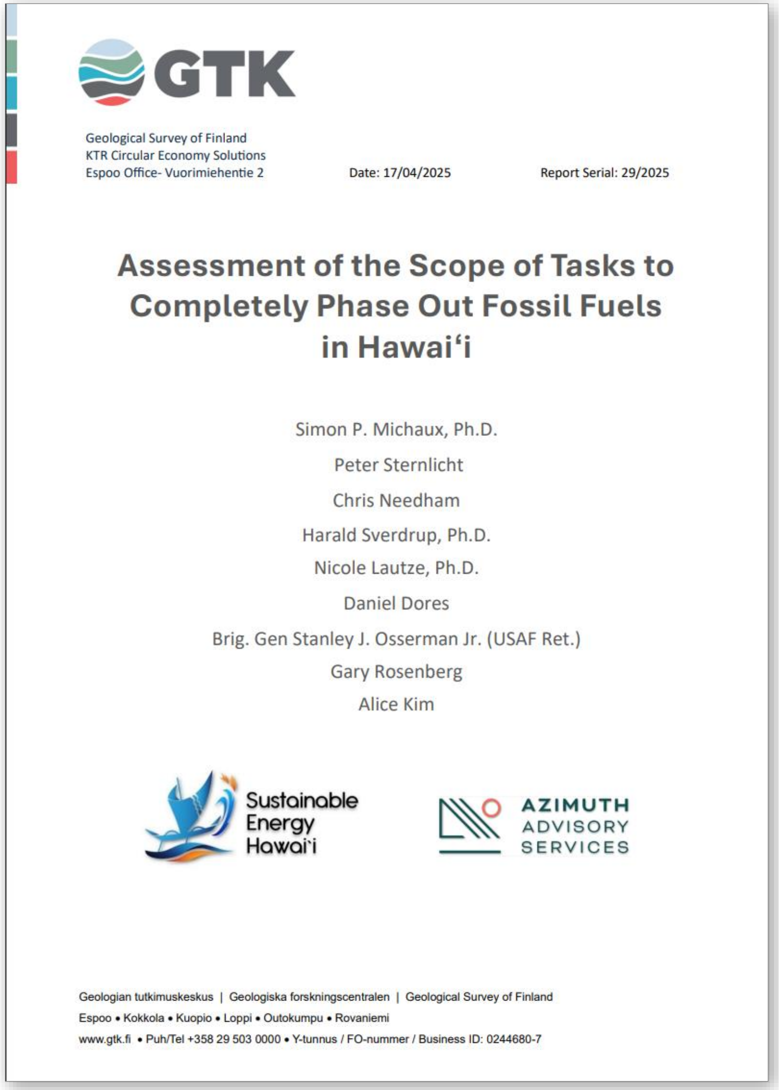
Simon P. Michaux
Peter Sternlicht

Why this study, why Hawai’i

- What is a sensible plan to phase out fossil fuels?
  - *The Green Transition*
- If the conventional plan won’t work, what might?
- How big is the Circular Economy and how does it relate to the Green Transition?
- What kind of resources do we need to do this and what kind?
- This is the third in the “Assessment to phase out fossil fuels” series
- The plan was to do one of these for each Nordic country
  - *Finland, Sweden, Norway, Demark, Iceland, Greenland*
- Develop this methodology for a region that has different challenges to Finland
- Hawai’i is an isolated and discrete system that can be quantified
  - *Heavily dependent on fossil fuels, oil in particular*
  - *Economy not based in any industrial or commodity production capability*

Many ideas for this project are documented in full in GTK report 29/2025

- The viability of the Green Transition
  - *Full electrification – Scenario HA*
  - *Wind and solar power storage calculation*
  - *Hydrogen economy – Scenario HB*
  - *Biofuels– Scenario HC*
- The Circular Economy– Scenario HG (Appendix Gamma, γ)
  - *Recycling (Appendix Delta, Δ)*
  - *Pyrolysis of human sewage – syngas (Appendix Kappa, κ)*
  - *Production of diesel from pyrolysis of rubber tyres (Appendix Mu, μ)*
  - *Harvesting plastics from the sea (Appendix Nu, ν)*
- Degrowth – Scenario HF
- 100% food production with organic regenerative permaculture
  - *Scenario HH*
- The Purple Transition – Scenario HI
  - *Thorium fueled MSR units (Appendix Theta, θ)*
  - *Combustion, and recycling of pure iron powder (Appendix Iota, ι)*
  - *Resource Balanced Economy (Appendix Zeta, ζ)*
  - *New form of transport (Appendix Eta, η)*



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Assessment of the Scope of Tasks to Completely Phase Out Fossil Fuels in Hawai‘i

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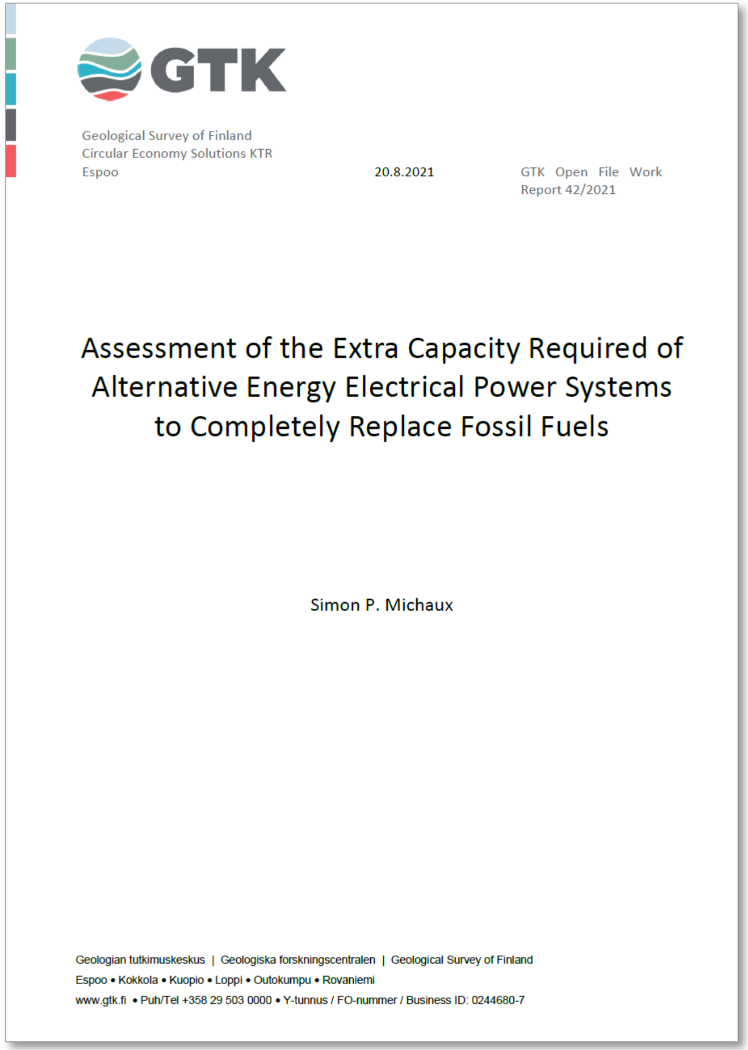
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Espoo

20.8.2021

GTK Open File Work Report 42/2021

Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels

Simon P. Michaux

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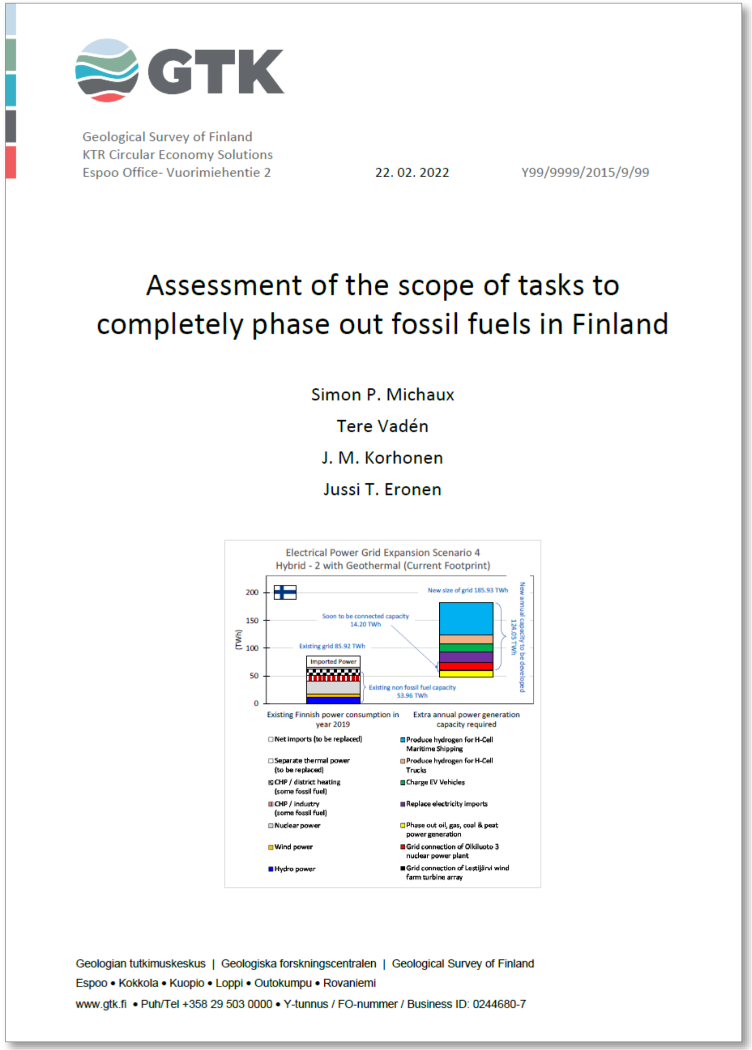
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Assessment of the scope of tasks to completely phase out fossil fuels in Finland

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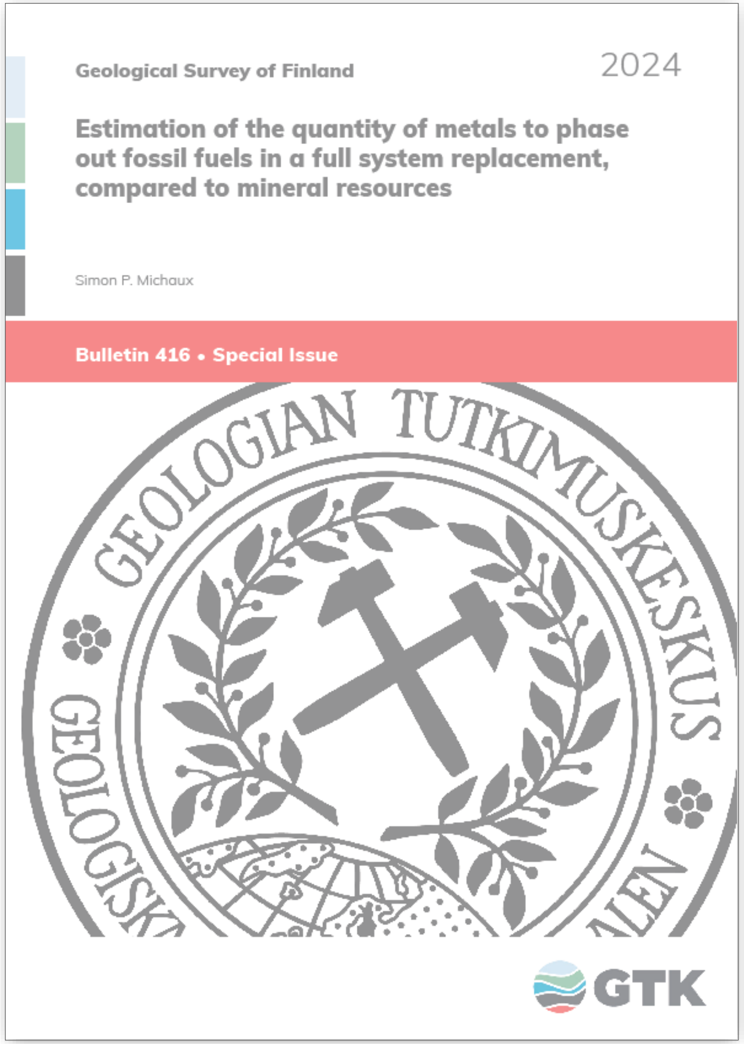
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2024

Estimation of the quantity of metals to phase out fossil fuels in a full system replacement, compared to mineral resources

Simon P. Michaux

Bulletin 416 • Special Issue

https://tupa.gtk.fi/julkaisu/bulletin/bt_416.pdf

Paradigm of report

- Map out the State of Hawai'i economy for 2019
- Fully electrify the whole system
  - *Electricity generation*
  - *Passenger cars, trucks, buses vans*
  - *Domestic maritime*
  - *International aviation*
- All fossil fuel systems (oil, gas & coal) are removed
- Model for 1 calendar year based on 2019 reported data
- Same physical activity and mechanical work done as in 2019 as a footprint

Assemble data for all practical options and technology paths to do this

The ideal, would be all problems and challenges are data mapped and are placed on the table, along with all possible solutions (conventional and unconventional). Around that table, all stakeholders are present, and a constructive dialogue then commences.

Electricity generation

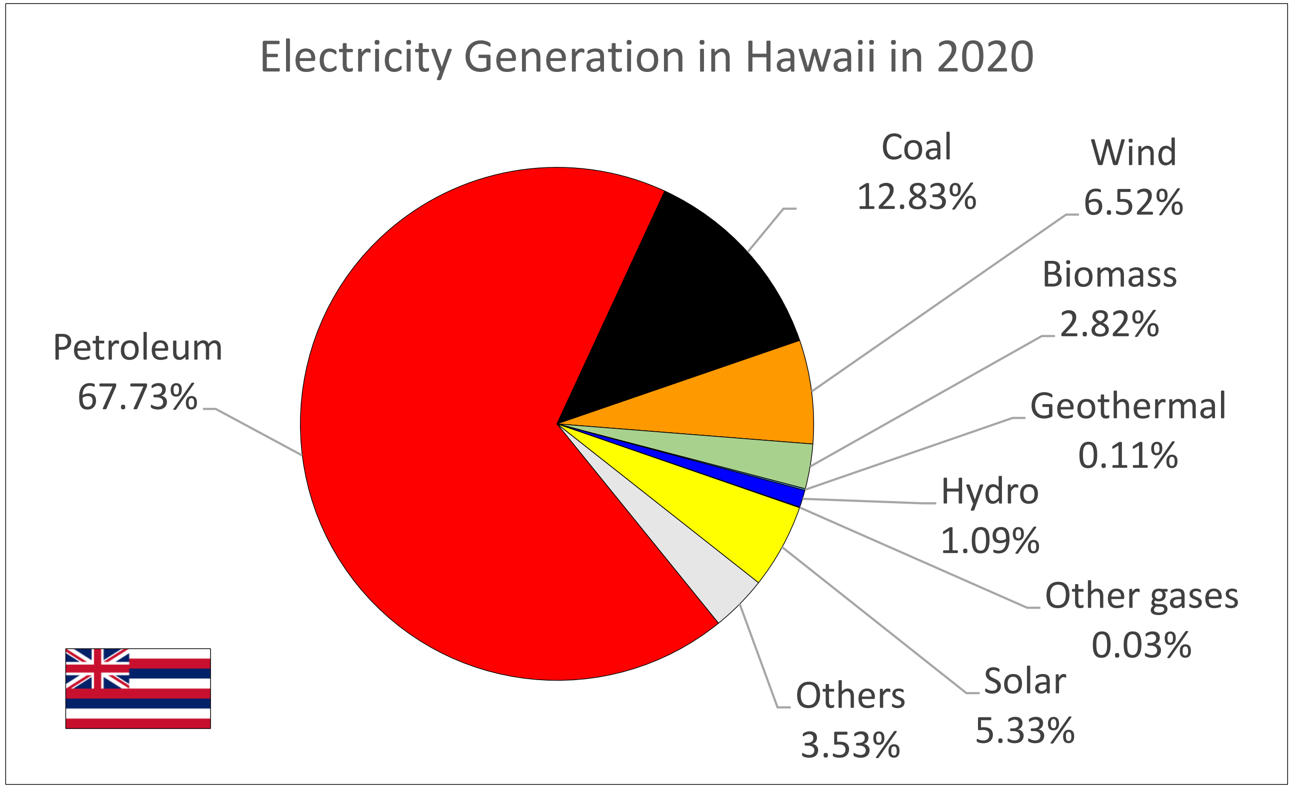


Figure 29. **ELECTRICITY GENERATION IN HAWAIʻI** in 2020 (Source: U.S. Department of Energy, Energy Information Administration, State Energy Data System (SEDS)

- 9.2 TWh of electricity sold

Transport

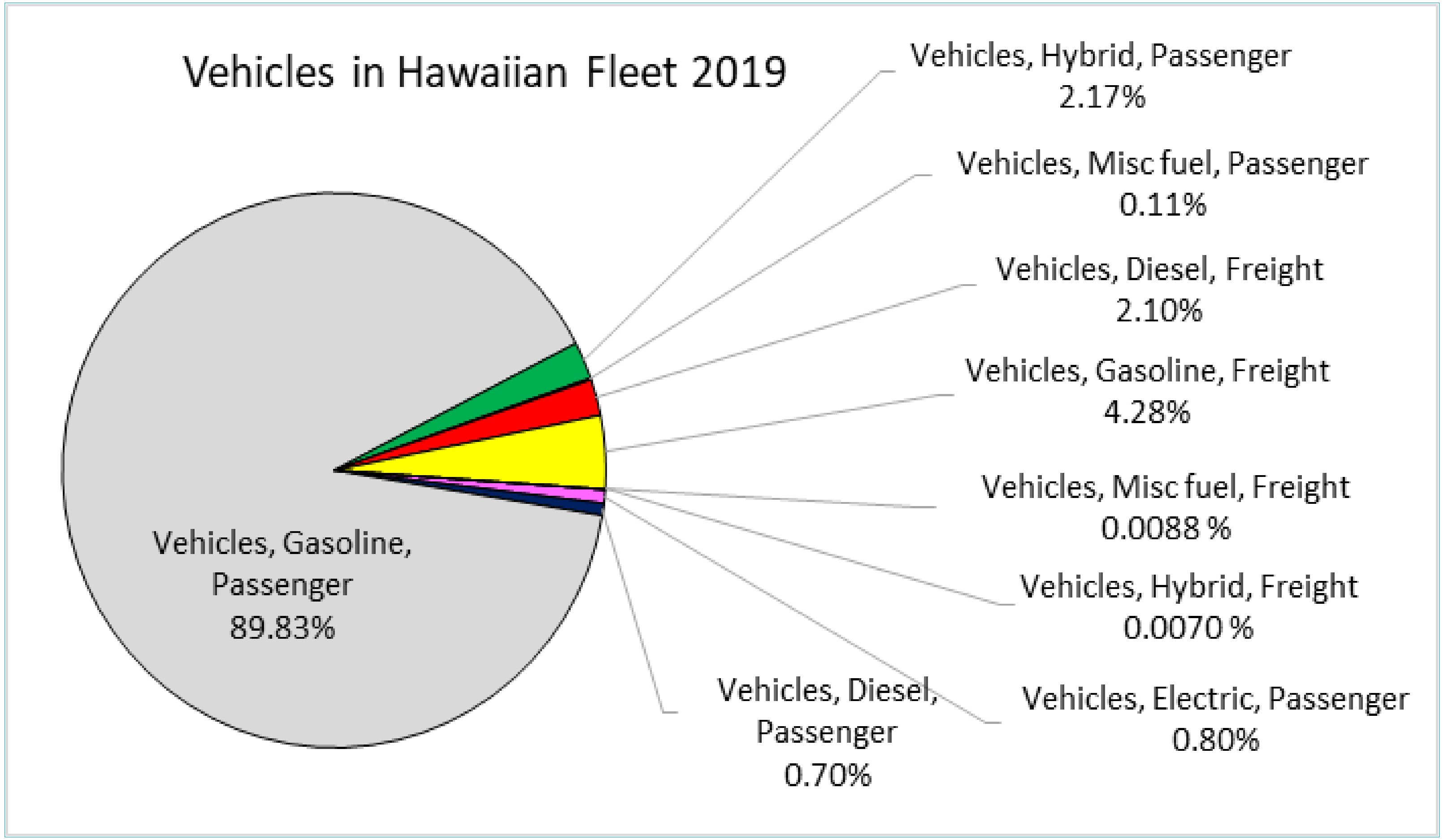


Figure 44. **VEHICLES IN HAWAIIAN TRANSPORT FLEET** in 2019
(Source: Hawaiʻi Energy Data DBEDT Data Warehouse)

- 507 million gallons of gasoline (land)
- 193.2 million gallons of diesel (land)
- 1.38 million gallons of gasoline (domestic maritime)
- 3.4 million gallons of diesel (domestic maritime)
- 271.7 million gallons of aviation fuel

- 36.9 TWh of thermal energy
- 6.2 TWh of mechanical work done

Transport

Table 11. **TAXABLE REGISTERED VEHICLES by Type and by County**, 2019

(Source: DBEDT Data Warehouse, Registered Vehicles, Taxable, 2019)

Type of vehicle	State total	County of Honolulu	County of Hawaii	County of Kauai	County of Maui
All Vehicles	1,308,344	809,128	218,487	90,019	190,710
Motor vehicles	1,279,843	795,949	210,358	86,650	186,886
Passenger vehicles 1/	1,038,642	662,567	163,483	63,932	148,660
Ambulances	101	49	20	13	19
Buses	2,146	1,569	319	90	168
Trucks 1/	194,263	101,179	40,608	20,174	32,302
Truck tractors	1,723	657	206	773	87
Truck cranes	3,831	3,457	194	77	103
Motorcycles, motorscooters 2/	39,137	26,471	5,528	1,591	5,547
Trailers and semi-trailers	28,501	13,179	8,129	3,369	3,824

1/ Vans, pickups, and other trucks under 6,500 lb. in personal use, legally classified as passenger vehicles, are included in the totals for trucks.

2/ Effective January 1, 2017 new mopeds were included in the motorcycles count, by December 31, 2017 all mopeds were included in the motorcycle count.

Source: Hawaii State Department of Transportation, Safe Communities Program, records.

Table 14. **STATE OF HAWAIʻI: DAILY DISTANCE TRAVELED BY VEHICLE CLASS** (2019 Reference Case)

Source: Hawaiʻi Department of Transportation, Highways Division, Planning Branch, Survey Section

Vehicle Class	Daily Distance 2019		Annual Distance - 2019	
	miles	(km)	miles	(km)
Motorcycles Class 1 [1]	261,289	420,504	95,370,485	153,483,918
Passenger Cars Class 2 [2]	20,526,122	33,033,591	7,492,034,530	12,057,260,819
Pickups/Vans Class 3 [3]	8,106,110	13,045,519	2,958,730,150	4,761,614,615
Buses Class 4 [4]	267,077	429,819	97,483,105	156,883,850
Trucks Class 5-7 [5, 6, 7]	667,430	1,074,124	243,611,950	392,055,430
Trucks Class 8-13 [8, 9, 10, 11, 12, 13]	244,049	392,759	89,077,885	143,356,960
Total	30,072,077	48,396,317	10,976,308,105	17,664,655,591

Source: Hawaii Department of TransportationHighways Division, Planning Branch, Survey Section

[1] 2 axels, 2 or 3 tires

[2] 2 axels, 4 tires, can have 1 or 2 axel

[3] 2 axels, 4 tire,
Can have 1 or 2 axel trailiers

[4] 2 or 3 axels, full length

5 thru 7

[5] 2 axels, 6 tires (dual rear tires), single unit

[6] 3 axels, single unit

[7] 3 axels, single unit

8 thru 13

[8] 3 or 4 axels, single trailer

[9] 5 axels, single trailer

[10] 6 or more axels, single trailer

[11] 5 or less or more axels, multiple trailers

[12] 6 axels, multiple trailers

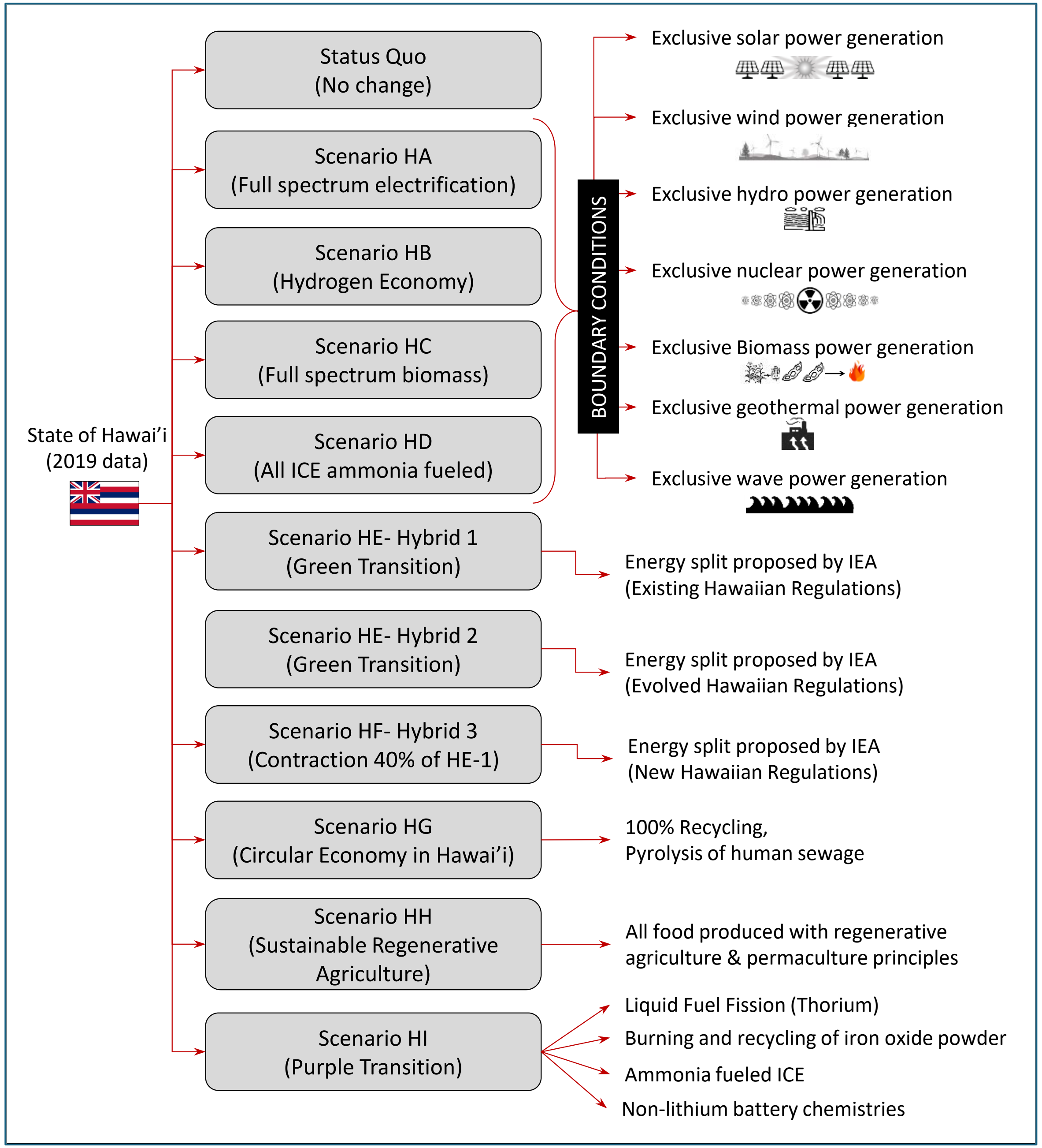
[13] 7 or more axels, multiple trailers

Table15. **LIQUID FUEL CONSUMPTION** by County, **REGISTERED VEHICLES BY FUEL TYPE** by County (2019)

Source: Hawaiʻi Energy Data DBEDT Data Warehouse 2019, DBEDT Databook 2020

Indicator (2019 Annual Values)	Units	Honolulu County	Hawaii County	Kauai County	Maui County	State Total
Liquid Fuel Tax Base						
Liquid Fuel Tax Base- Gasoline	Gallons	282,986,516	84,083,677	30,827,504	67,646,607	465,544,304
Liquid Fuel Tax Base- Diesel oil, Non-Hwy	Gallons	78,711,674	22,010,350	6,886,518	38,602,681	146,211,223
Liquid Fuel Tax Base- Diesel oil, Hwy Use	Gallons	25,748,586	11,968,755	3,271,489	6,009,152	46,997,982
Liquid Fuel Tax Base- LPG, Hwy Use	Gallons	5,694	1,179	1,477	595	8,945
Liquid Fuel Tax Base- Other fuel	Gallons	1,442,303	26,853,581	12,873,045	266,051	41,434,980
Vehicles - Taxible by Fuel Type						
Reg. Vehicles, Taxable- Electric, Passenger	Vehicles	7,273	526	303	1,122	9,225
Reg. Vehicles, Taxable- Diesel, Passenger	Vehicles	2,710	2,918	1,006	1,427	8,061
Reg. Vehicles, Taxable- Gasoline, Passenger	Vehicles	614,915	180,687	77,639	162,130	1,035,372
Reg. Vehicles, Taxable- Hybrid, Passenger	Vehicles	17,029	3,180	1,105	3,646	24,959
Reg. Vehicles, Taxable- Misc fuel, Passenger	Vehicles	540	352	84	287	1,262
Reg. Vehicles, Taxable- Electric, Freight	Vehicles	14	0	0	1	15
Reg. Vehicles, Taxable- Diesel, Freight	Vehicles	11,431	6,848	2,249	3,690	24,218
Reg. Vehicles, Taxable- Gasoline, Freight	Vehicles	33,931	7,173	1,892	6,300	49,296
Reg. Vehicles, Taxable- Hybrid, Freight	Vehicles	73	3	2	4	81
Reg. Vehicles, Taxable- Misc fuel, Freight	Vehicles	89	5	1	7	102

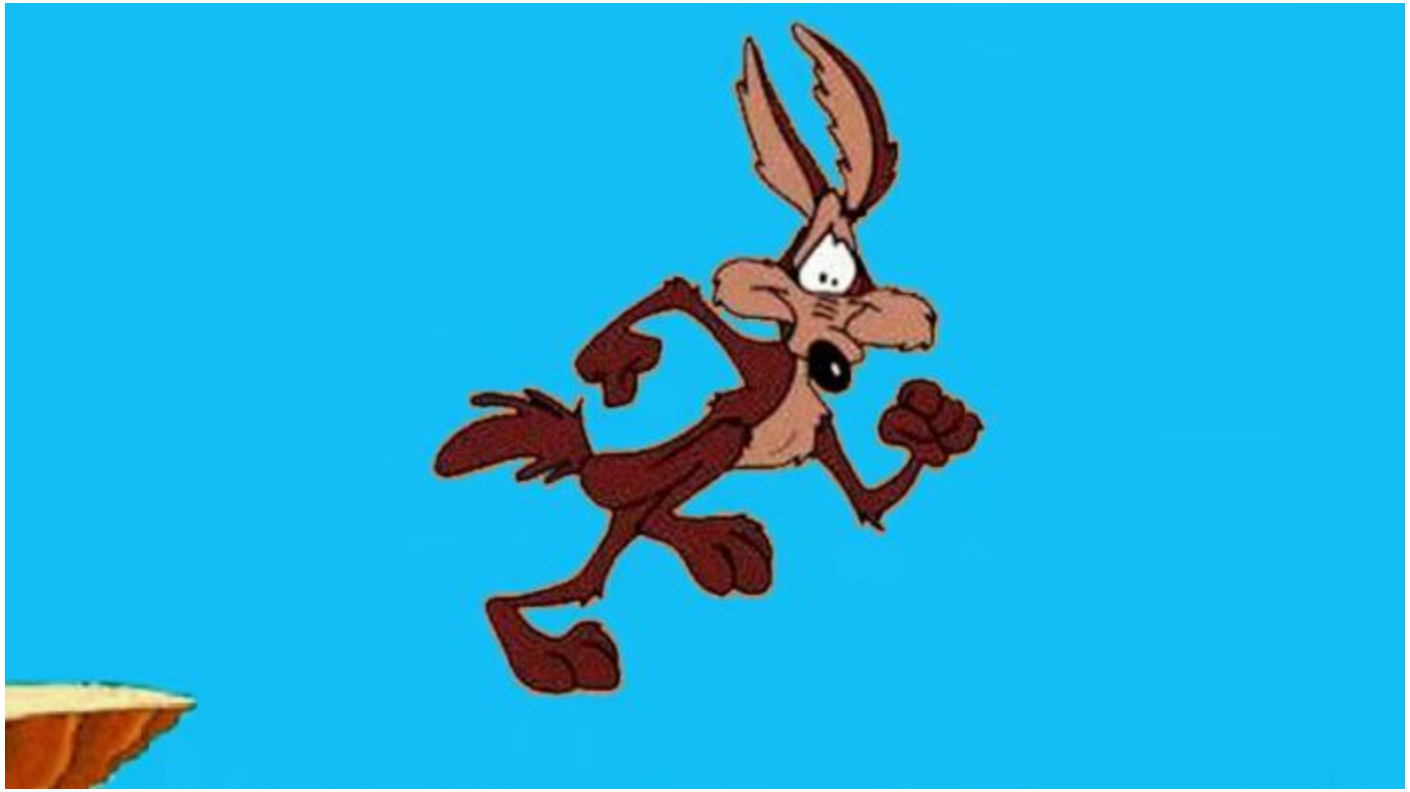
Source: Hawaiʻi Energy Data DBEDT Data Warehouse 2019, DBEDT Databook 2020



Same footprint and physical work done as in 2019

- Existing electrical demand
- Gasoline based transport
- Diesel based transport
- Domestic Maritime
- International aviation

Figure 50. **SCENARIOS FOR POSSIBLE FUTURE DEVELOPMENT IN THE STATE OF HAWAI'I**



Scenario H0: No action is taken

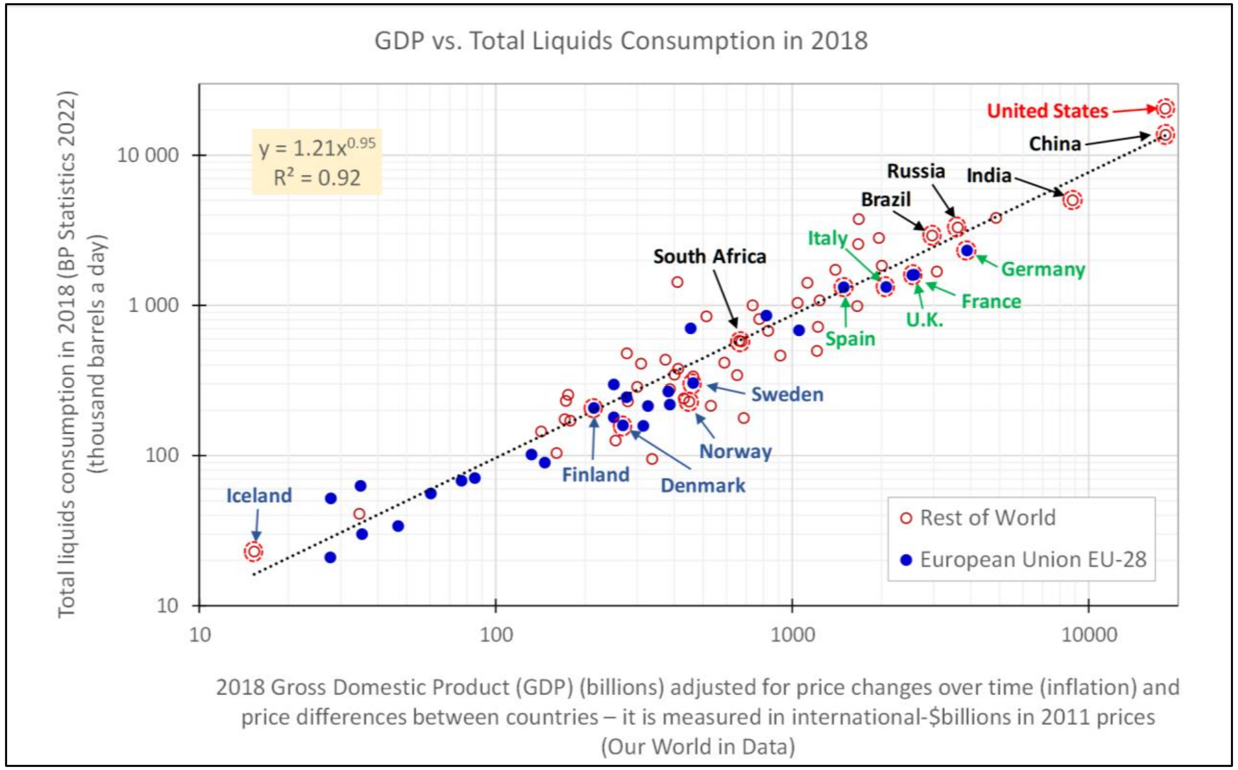


Figure 138. **GDP BY COUNTRY VS. TOTAL LIQUIDS CONSUMPTION BY COUNTRY** (2018)
(Source: Labyrinth Consulting, Art Berman, Our World in Data)

Scenario H0: No action is taken

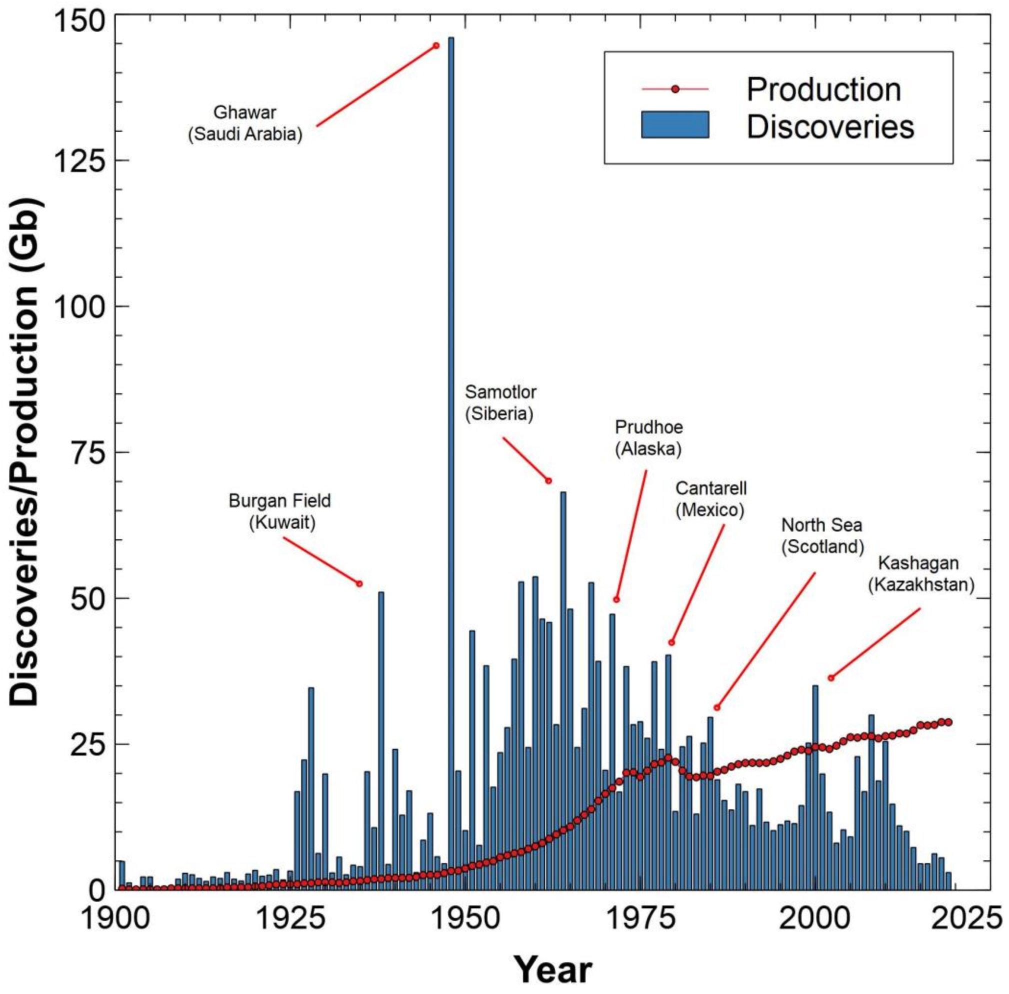
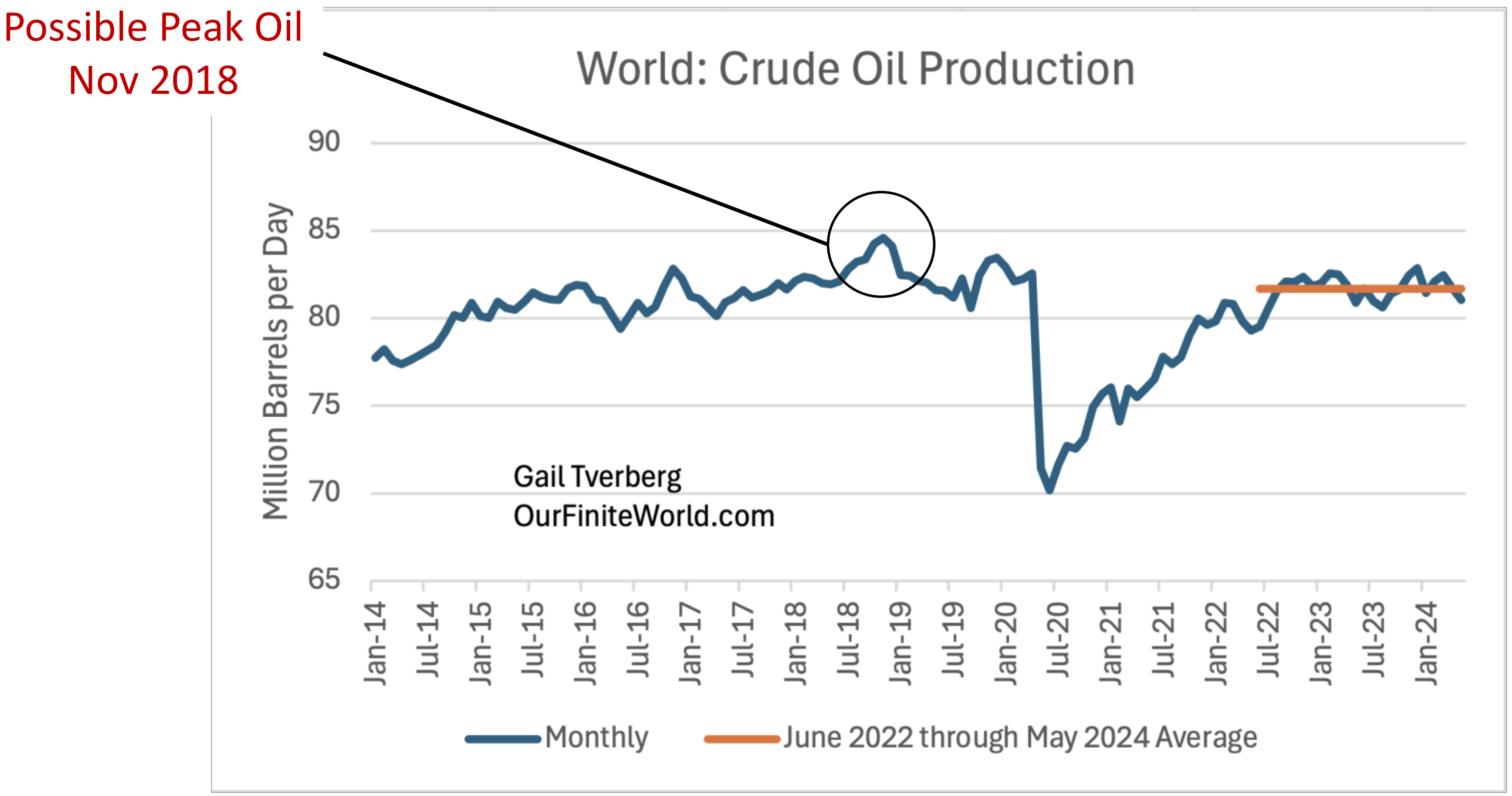


Figure R9, Appendix R. Conventional oil resource discovery 1920-2020
(Source: John Peach, data from Laherre et al 2022, Court & Fizaine 2017, BP Energy Statistics 2022)

Scenario H0: No action is taken



https://ourfiniteworld.com/2024/09/11/crude-oil-extraction-may-be-well-past-peak/

81% of existing oil reserves are being annually depleted at a rate ranging between 5 to 15%

Scenario HA: ‘Boundary Condition’, All Systems are Electrified, All ICE Transport is Substituted with Electric Vehicles (EV)

- All transportation was electric propulsion powered by a lithium-ion battery
- All conventional non fossil fuel power generation systems were looked at and exclusive context for electricity production
- It was found that it was more sensible to have a combination of transportation technology systems, where each one was matched to its engineering efficiency window
- It was not sensible to have all transport as battery supported electric vehicles

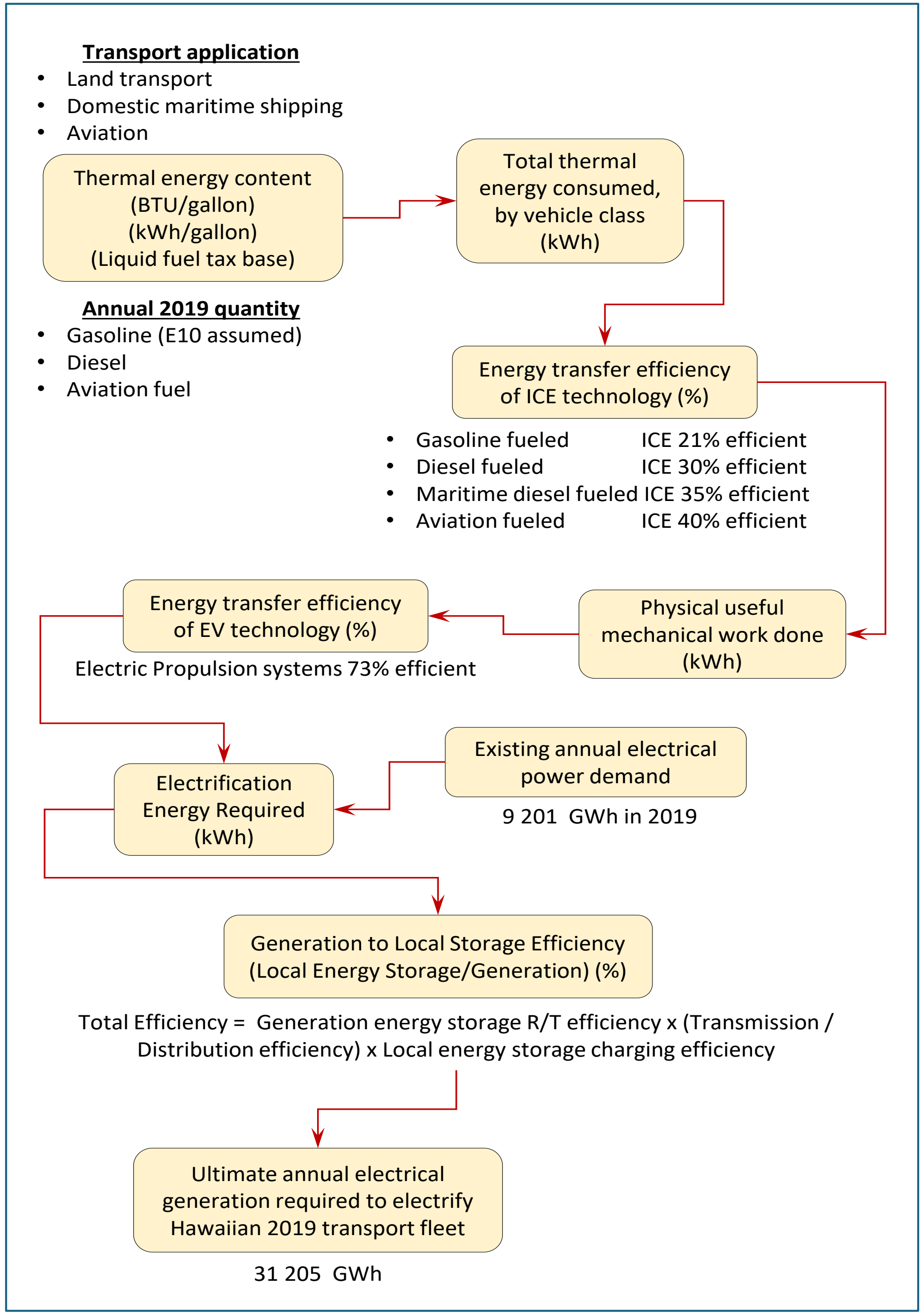


Figure 59. **ELECTRIFICATION OF THE ICE TRANSPORT FLEET CALCULATION FLOW CHART**

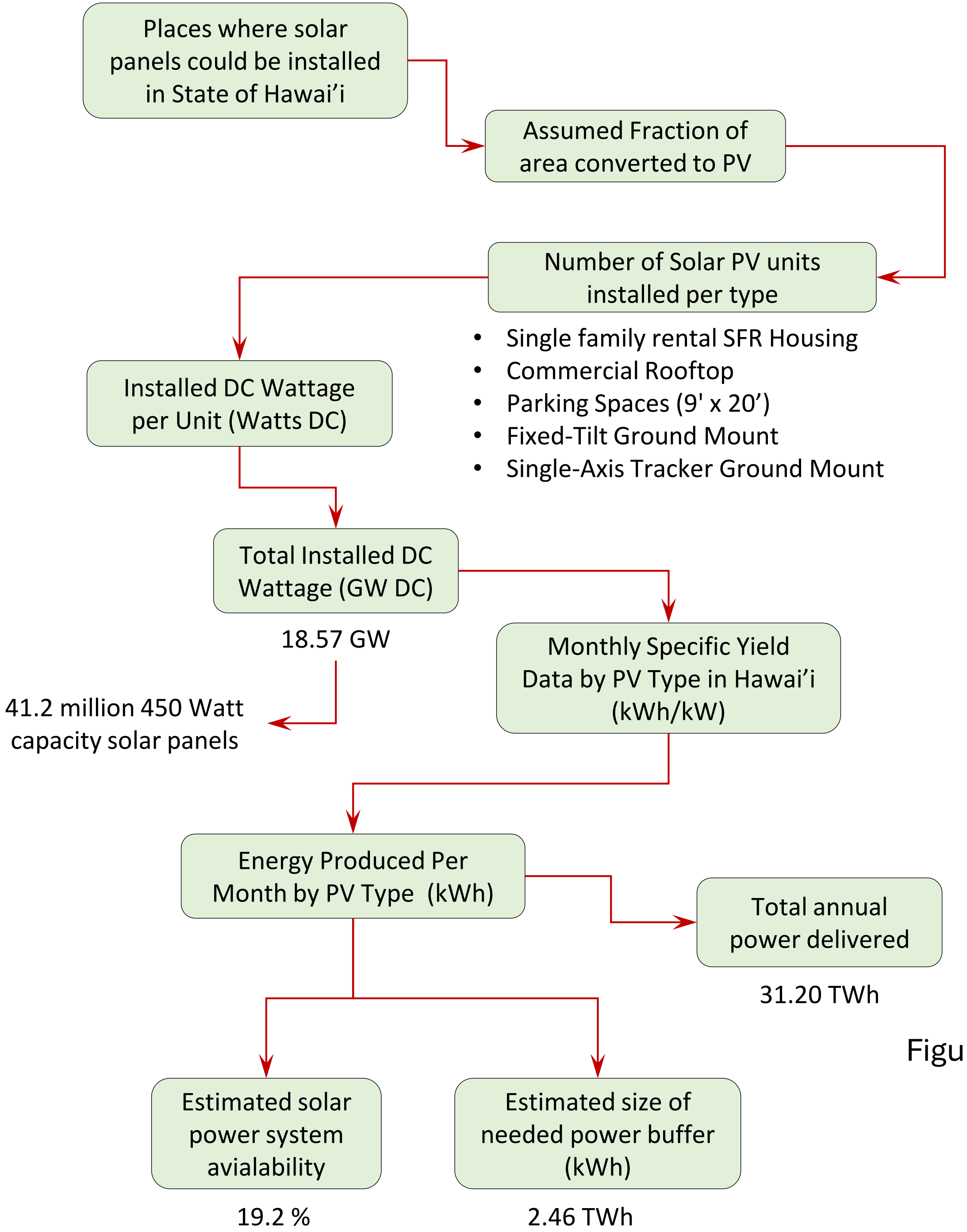


Figure 63. **SIZE AND PERFORMANCE METRICS OF THE PROPOSED HAWAIIAN SOLAR PV GRID CALCULATION FLOW CHART**

Stationary power storage

Table 40. **MONTHLY SPECIFIC YIELD DATA BY PV TYPE IN HAWAI'I**
in the proposed Hawaiian solar power grid

Monthly Specific Yield Data by PV Type in Hawai'i	SFR Housing ♣ (kWh/kW)	Commercial Rooftop ♦ (kWh/kW)	Parking Spaces (9' x 20') ♥ (kWh/kW)	Fixed-Tilt Ground Mount ♠ (kWh/kW)	Single-Axis Tracker Ground Mount ψ (kWh/kW)
Jan	1.2E+02	1.1E+02	1.1E+02	1.1E+02	134.5
Feb	1.1E+02	1.0E+02	1.0E+02	1.1E+02	130.2
Mar	1.4E+02	1.4E+02	1.4E+02	1.4E+02	169.9
Apr	1.5E+02	1.5E+02	1.5E+02	1.5E+02	178.0
May	1.5E+02	1.6E+02	1.6E+02	1.6E+02	201.5
Jun	1.6E+02	1.7E+02	1.7E+02	1.7E+02	209.7
Jul	1.6E+02	1.7E+02	1.7E+02	1.7E+02	216.3
Aug	1.6E+02	1.6E+02	1.7E+02	1.6E+02	207.1
Sep	1.5E+02	1.5E+02	1.5E+02	1.5E+02	187.1
Oct	1.4E+02	1.3E+02	1.3E+02	1.3E+02	157.3
Nov	1.1E+02	1.0E+02	1.0E+02	1.1E+02	124.7
Dec	1.1E+02	9.6E+01	9.6E+01	1.0E+02	122.9
Annual	1.7E+03	1.6E+03	1.6E+03	1.7E+03	2,039.2

Notes:

Simulations Run with NREL SAM 2022.11.21
Location (SAM weather file database): 21.29N, -157.86W (Oahu)
Panel Efficiency Assumed to be 20.5 W/sqft

Estimate shows that single-axis trackers take up ~60% more land for fixed-tilt systems for the same energy generation.

Policy supporting "net zero" housing construction can focus new builds on increasing solar PV installations.

Parking Spaces are an under-utilized asset for PV in Hawai'i, providing 6.6 out of the modelled 31 TWh. There are an estimated 9,000 acres of parking spaces in Hawai'i.

This analysis is done for annual production, but energy storage in the state will likely only be one month in duration or less. For this reason, PV should be oversized (~30%?) to match the monthly demand. However, better demand data is necessary.

♣ Single-family rentals, SFR, Assumed 15 degree roof slope and 33% each azimuth: 135 degrees, 180 degrees, 225 degrees.

♦ 85% GCR, E-W Layout (GCR - Ground Coverage Ratio)
♥ E-W Layout
♠ 50/50 mix of: 10 degree tilt @ 75% GCR and E-W @ 85% GCR
ψ Assumed 42% GCR overall.

Table 41. **ESTIMATED ELECTRICAL POWER DELIVERED BY MONTH**
for the proposed Hawaiian solar power grid in Scenario HA

Energy Produced Per Month by PV Type	SFR Housing ♣ (kWh)	Commercial Rooftop ♦ (kWh)	Parking Spaces (9' x 20') ♥ (kWh)	Fixed-Tilt Ground Mount ♠ (kWh)	Single-Axis Tracker Ground Mount ψ (kWh)	Total All Systems Scenario HA (kWh)
Jan	2.7E+08	2.2E+07	4.3E+08	1.2E+09	1.5E+08	2.11E+09
Feb	2.5E+08	2.1E+07	4.2E+08	1.2E+09	1.5E+08	2.04E+09
Mar	3.2E+08	2.8E+07	5.6E+08	1.5E+09	1.9E+08	2.64E+09
Apr	3.2E+08	3.0E+07	6.0E+08	1.6E+09	2.0E+08	2.76E+09
May	3.4E+08	3.2E+07	6.5E+08	1.7E+09	2.3E+08	2.98E+09
Jun	3.5E+08	3.4E+07	6.9E+08	1.8E+09	2.4E+08	3.12E+09
Jul	3.7E+08	3.5E+07	7.0E+08	1.9E+09	2.4E+08	3.21E+09
Aug	3.6E+08	3.4E+07	6.7E+08	1.8E+09	2.3E+08	3.10E+09
Sep	3.4E+08	3.0E+07	6.0E+08	1.7E+09	2.1E+08	2.84E+09
Oct	3.0E+08	2.6E+07	5.1E+08	1.4E+09	1.8E+08	2.45E+09
Nov	2.5E+08	2.1E+07	4.1E+08	1.2E+09	1.4E+08	2.00E+09
Dec	2.5E+08	2.0E+07	3.9E+08	1.1E+09	1.4E+08	1.93E+09
Annual	**3.7E+09**	**3.3E+08**	**6.6E+09**	**1.8E+10**	**2.3E+09**	**3.12E+10**
					Total annual power delivered	**31.20 TWh**

Notes:

Simulations Run with NREL SAM 2022.11.21
Location (SAM weather file database): 21.29N, -157.86W (Oahu)
Panel Efficiency Assumed to be 20.5 W/sqft

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♥ E-W Layout
♠ 50/50 mix of: 10 degree tilt @ 75% GCR and E-W @ 85% GCR
ψ Assumed 42% GCR overall.

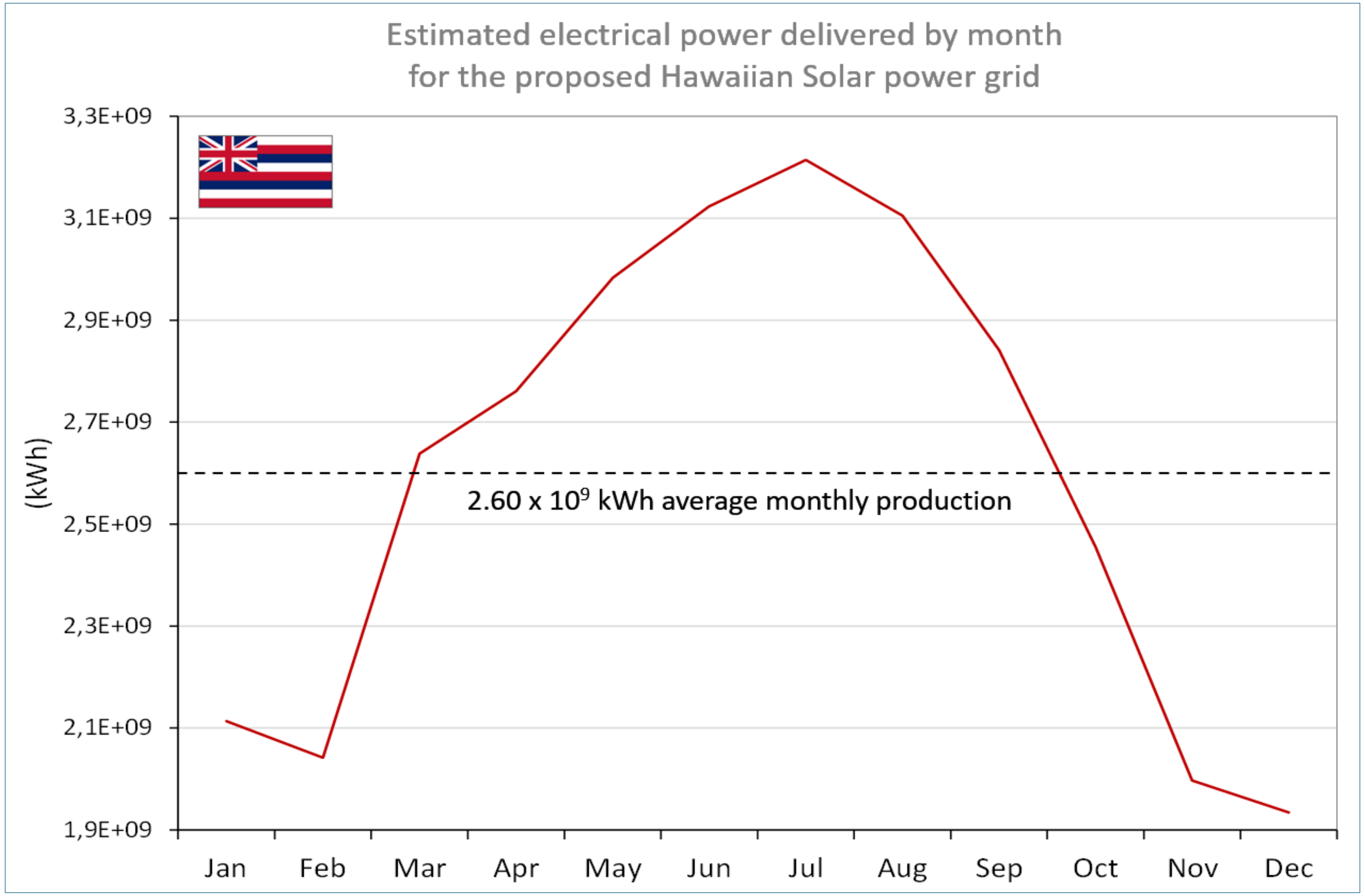


Figure 64. **ESTIMATED ELECTRICAL POWER DELIVERED BY MONTH**
for the proposed Hawaiian solar power grid in Scenario HA

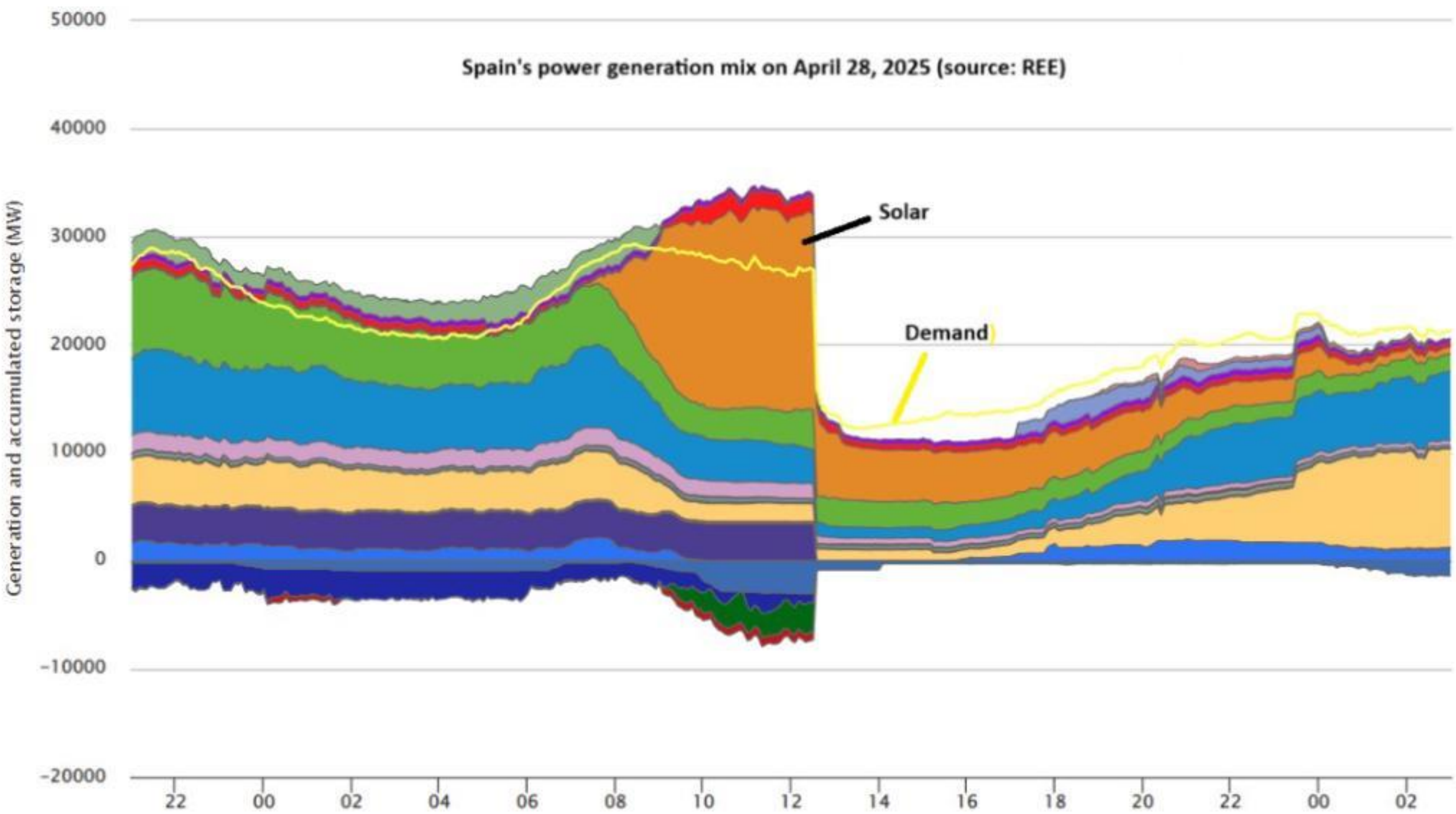
Table 43. **ESTIMATED SIZE OF THE BUFFER NEEDED FOR SOLAR POWER GENERATION, AND SOLAR POWER SYSTEM AVAILABILITY** in Scenario HA

Energy Produced Per Month by PV Type	Days in month for a standard calendar year	Electricity production assuming a 100% solar radiance efficiency Δ	Estimated electrical power delivered by month for the proposed Hawaiian solar power grid	Electrical power excess/shortfall below grid average of 2.60 x 10^9 kWh/month		Estimated solar power specific yield Scenario HA
	(number)	(kWh)	(kWh)	(kWh)	(kWh)	(%)
Jan	31	1.38E+10	2.11E+09	-4.87E+08		15.3 %
Feb	28	1.25E+10	2.04E+09	-5.59E+08		16.4 %
Mar	31	1.38E+10	2.64E+09		3.75E+07	19.1 %
Apr	30	1.34E+10	2.76E+09		1.60E+08	20.7 %
May	31	1.38E+10	2.98E+09		3.83E+08	21.6 %
Jun	30	1.34E+10	3.12E+09		5.23E+08	23.4 %
Jul	31	1.38E+10	3.21E+09		6.14E+08	23.3 %
Aug	31	1.38E+10	3.10E+09		5.04E+08	22.5 %
Sep	30	1.34E+10	2.84E+09		2.41E+08	21.3 %
Oct	31	1.38E+10	2.45E+09	-1.46E+08		17.8 %
Nov	30	1.34E+10	2.00E+09	-6.04E+08		14.9 %
Dec	31	1.38E+10	1.93E+09	-6.66E+08		14.0 %
Annual total			**3.12E+10**	**-2.46E+09**	**2.46E+09**	
Monthy average			**2.60E+09**			**19.2 %**

Δ Assumed installed capacity of total proposed Hawaiian solar powered grid was 18.57 GW

Across the year, there was a shortfall of 2.46 TWh (almost 1 month of capacity) over a sustained 5 months. Taking the average number of days in a month (30.4), this would be 28.8 days of power storage, or 2.46 TWh of capacity required in this buffer. Effectively, that quantity of power would need to be stored for five months.

28 April 2025



This puts to rest the idea that a 3 times build out of solar, and wind will negate the need of a power storage buffer for renewable energy

Scenario HB: ‘Boundary Condition’: All Systems are Electrified: All ICE Transport Substituted with Fuel Cell Electric Vehicles (FCEV)

- All transportation was electric propulsion powered by a hydrogen fuel cell
- The annual quantity of hydrogen required to do this was calculated, as was the electrical power required produced the hydrogen
- Once again, all conventional non fossil fuel power generation systems were looked at and exclusive context for electricity production

Scenario HC: ‘Boundary Condition’, ALL SYSTEMS are Biomass Supported

- All electrical power demand was delivered through the combustion of biomass in a combined heat and power (CHP) plant
- All ICE technology was retrofitted to be powered with biofuel
- The quantity of biomass needed, and the area of arable land required to annually grow the biomass was calculated
- It was found that the required arable land area to grow the biomass feedstock (wood, corn, and soybean), far exceeded what was possible with the land that was available
- While all non-fossil fuel systems have their place, and have they fit for purpose application, the large-scale production of biofuels with these conventional feedstocks is simply not viable

Scenario HD: Boundary Condition, All ICE technology Substitutes Ammonia Fuels for Liquid Fossil Fuels

- All ICE technology was retrofitted and fueled with ammonia
- The annual quantity of hydrogen, and the quantity of electrical power required to produce the ammonia was calculated
- Once again, all conventional non fossil fuel power generation systems were looked at and exclusive context for electricity production
- This scenario proved to be the most energy intensive by far
- Ammonia is a useful fuel to consider, but certainly not for all applications
- Ammonia fuel may be the most practical way to maintain the international maritime shipping industry

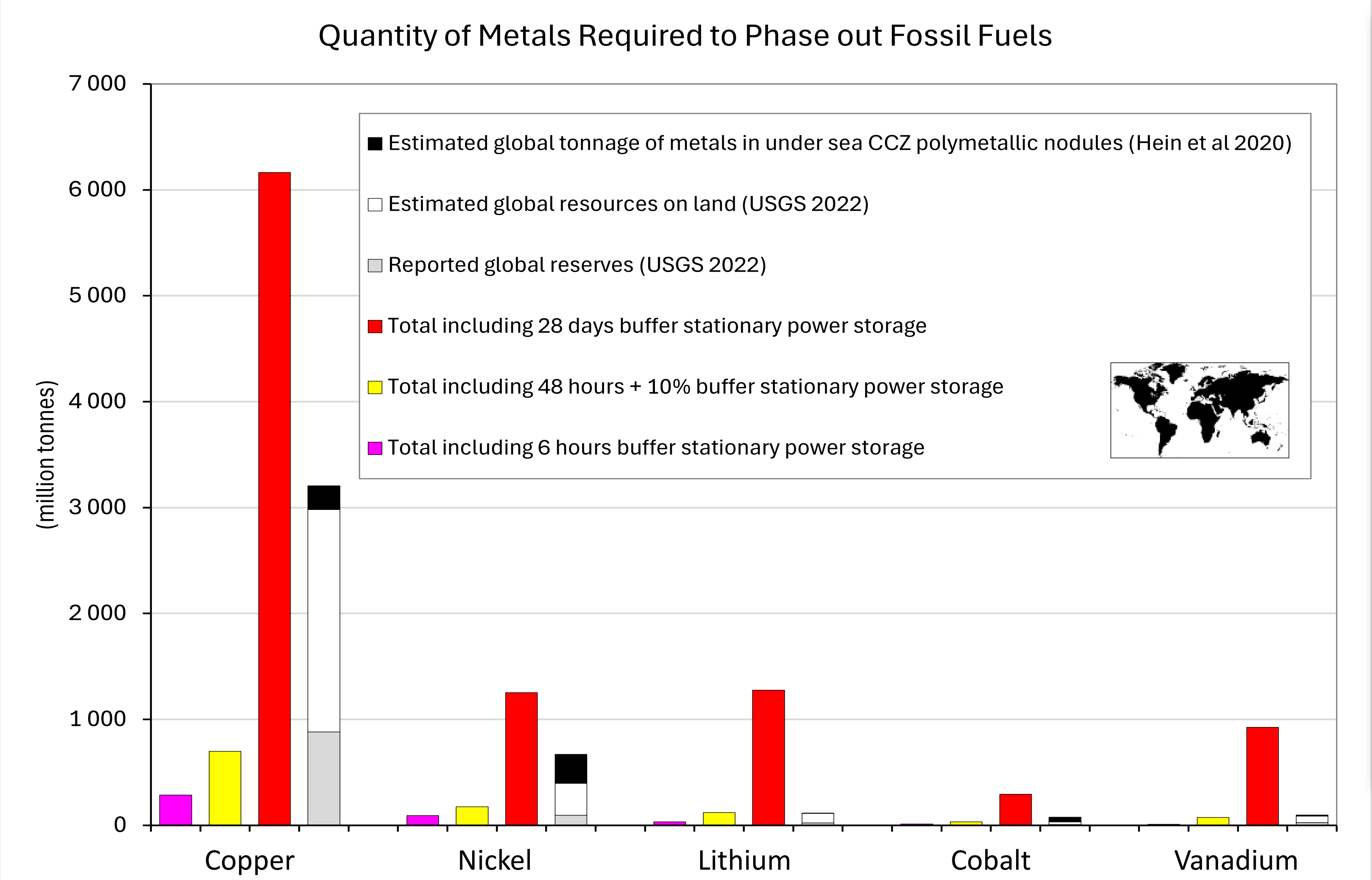
Scenario HE: Hybrid 1 – The Green Transition – Existing Hawai‘i Regulatory Framework

- The Green Transition was used as a paradigm template to phase out fossil fuels
- All short-range light vehicles were EV’s
- All long-range heavy vehicles were considered to be hydrogen fuel cell FCEV H2-cell vehicles
- The power generation energy mix used was what the IEA proposed for 2050 but applied in the State of Hawai’i
  - *That is, the Green Transition energy mix, using what current Hawaiian legislation and regulations would allow*
  - *This outcome meant the solar PV systems accounted for 80% of the energy mix.*
- A logistical limitation shown in this scenario was the need for stationary power storage to support wind and solar PV electricity generation systems

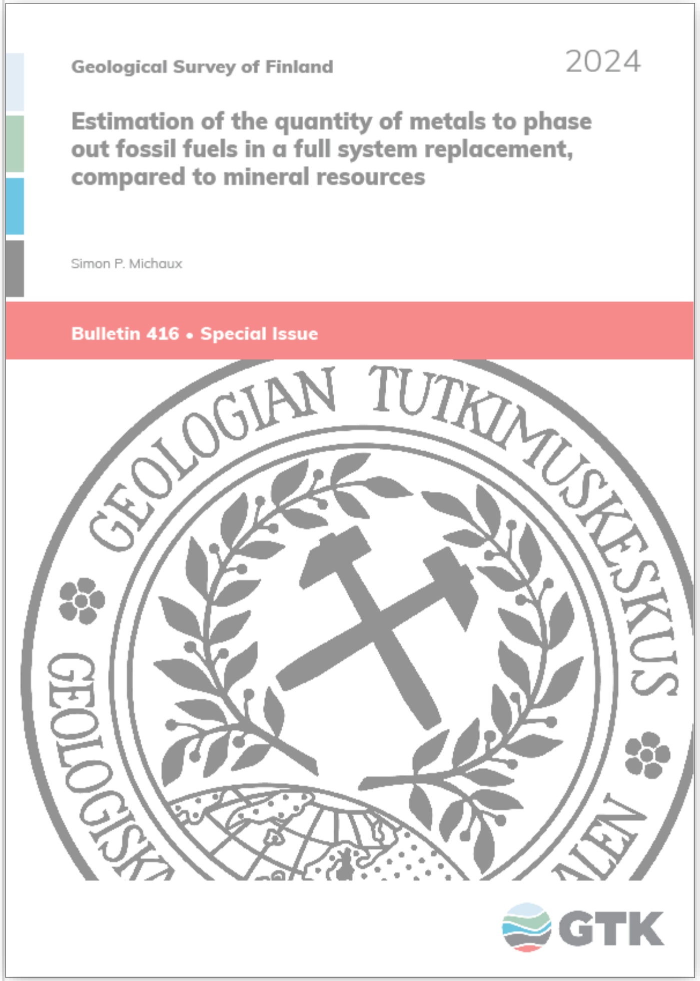
Scenario HE: Hybrid 2 – Modernized Regulations

- To examine the implications of a change in Hawaiian legislation and regulations
- The electricity demand was the same as modelled in Scenario HE-Hybrid 1, but different electrical power generation systems were applied
- It was assumed that regulations would allow
  - *the installation of a conventional nuclear power plant*
  - *the scale up of geothermal power*
  - *the application of wave and ocean energy systems*
  - *the application of especially bread perennial grass species (XanoGrassTM) used as feedstock for biofuels.*

Reported Mineral Reserves + Estimated Resources + Undersea Resources



(USGS Mineral Statistics 2023, Hein *et al.* 2020)



https://tupa.gtk.fi/julkaisu/bulletin/bt_416.pdf

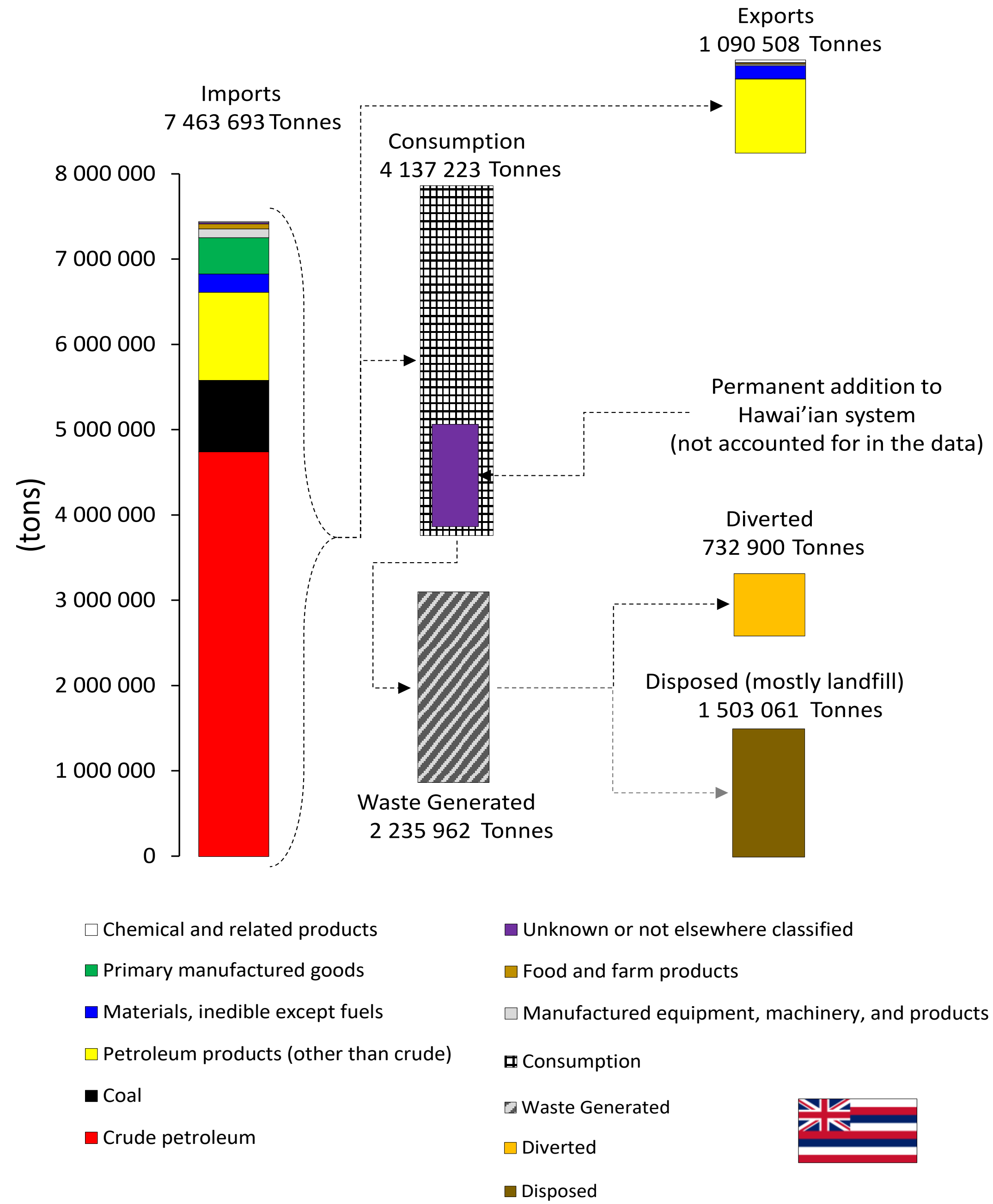
Scenario HF: Hybrid 3, Resource Depletion

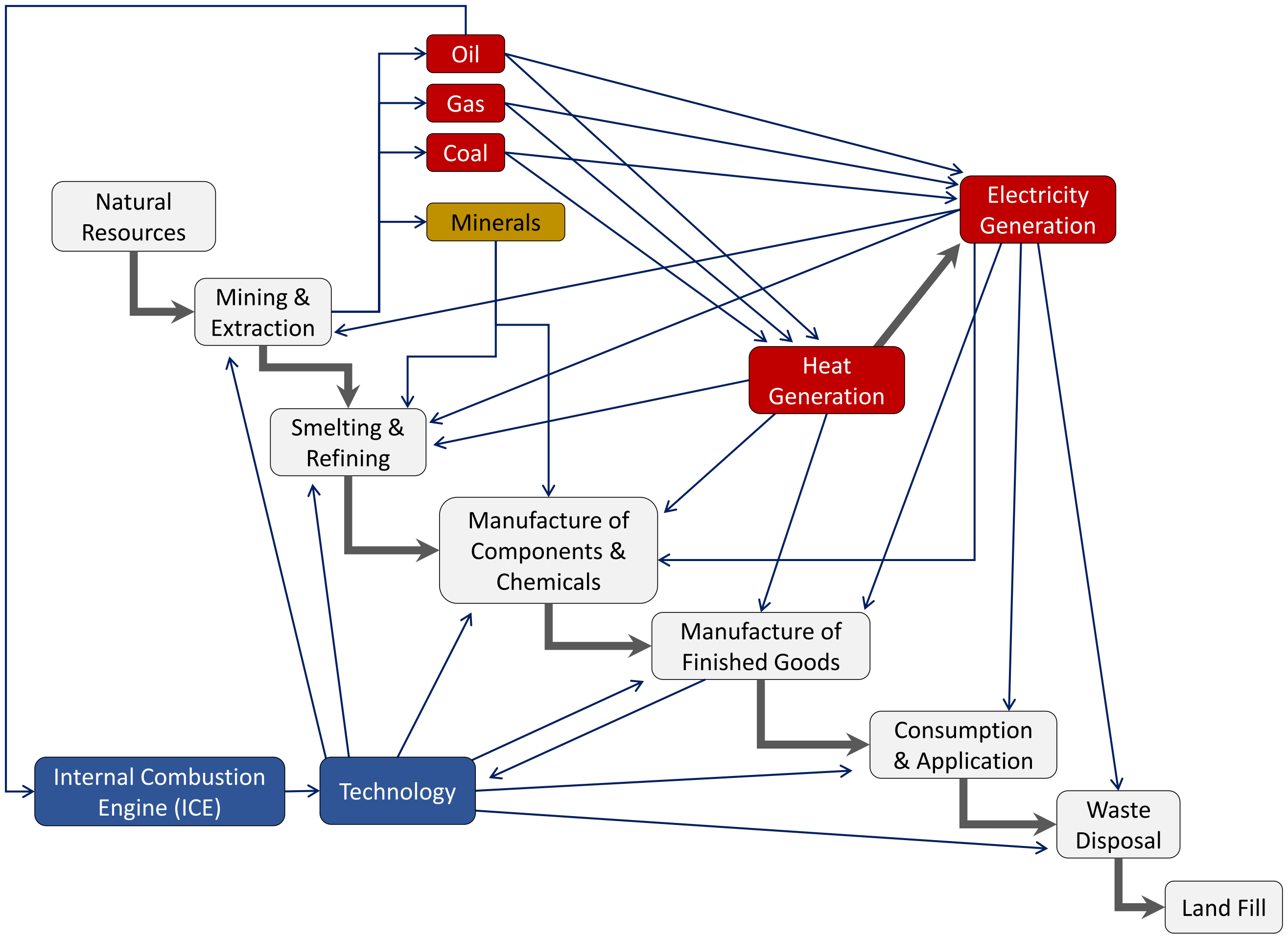
- To model a 6 month disruption to maritime shipping and aviation imports
- Hawai’i would have to be more self reliant and have a smaller footprint in resource consumption in comparison to domestic capability
- The Hawaiian system was contracted by 40%

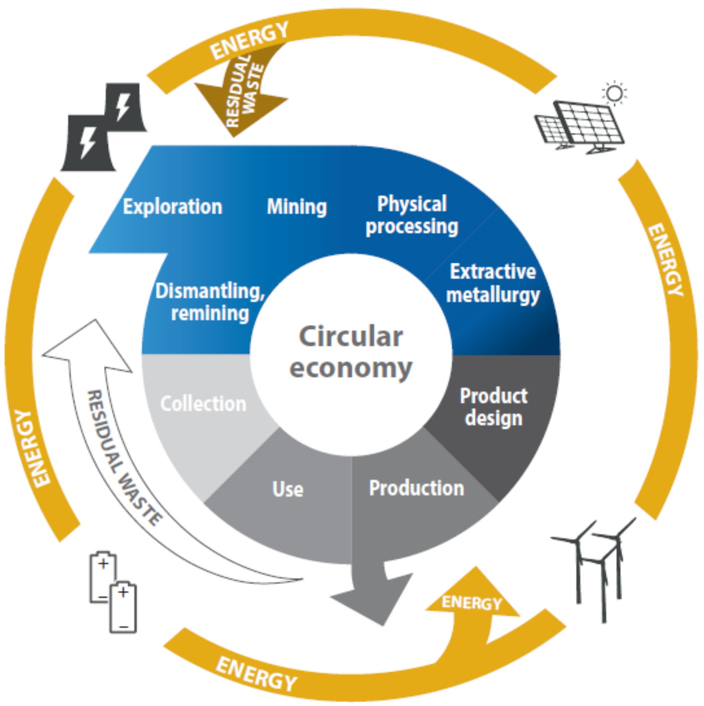
Scenario HG: The Circular Economy

- The Circular Economy was applied in full
- All annual waste produced by Hawaiian society was collected and recycled
  - *The performance characteristics of a network of recycling plants in the United Kingdom we used to estimate the mass quantities of useful raw materials that will be generated each year from the State of Hawai'i, if this was done*
- As there is very little manufacture in the State of Hawai'i, it was assumed that all recycled material was transported by maritime ship to Southeast Asia where it could all be inserted into the beginning of the manufacture value chain
- The size of the green transition could now be compared directly to the size of the circular economy, by comparing the required infrastructure between Scenario HE-Hybrid 1 and Scenario HG
  - *It was observed that the infrastructure required for the green transition was orders of magnitude larger than the infrastructure required for a fully applied Circular Economy.*

Mass Flows Imports/Exports in State of Hawai'i for 2016

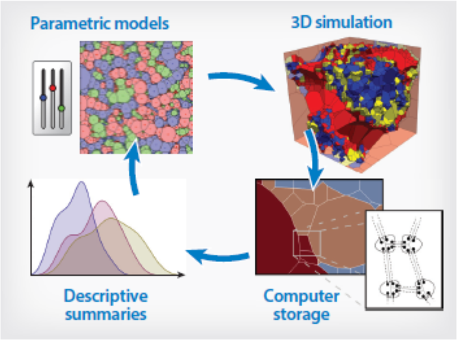






Mining and physical processing

Ore mineralogy



Extractive metallurgy

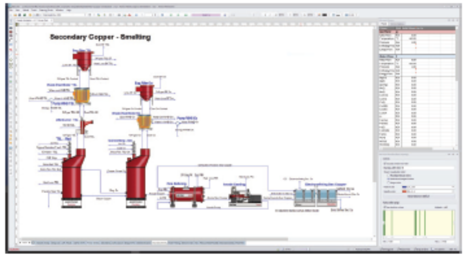
Concentrate, eWaste, residue, end-of-life products, etc., processing

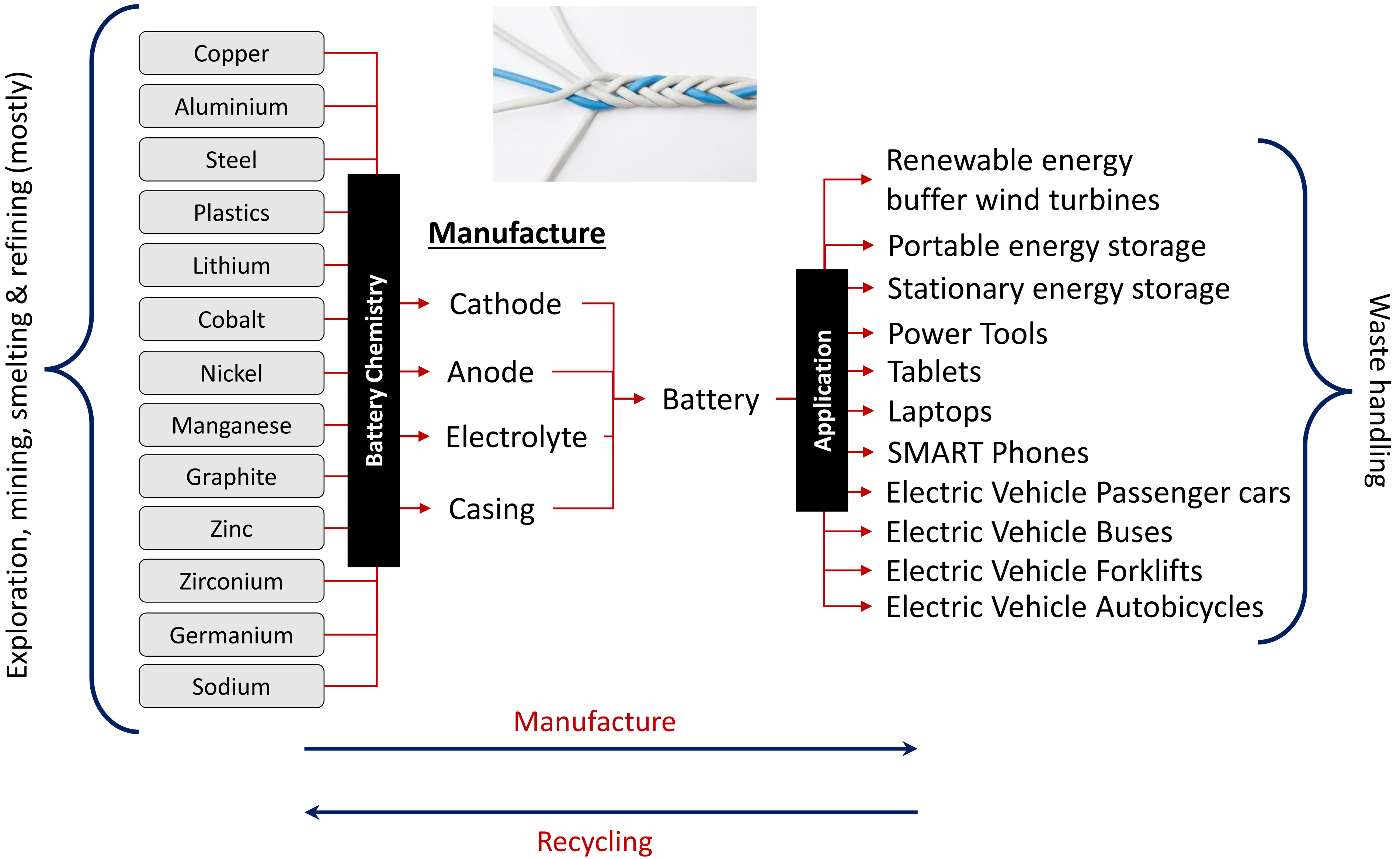
Product design: design for recycling

Bill of material and full material declaration

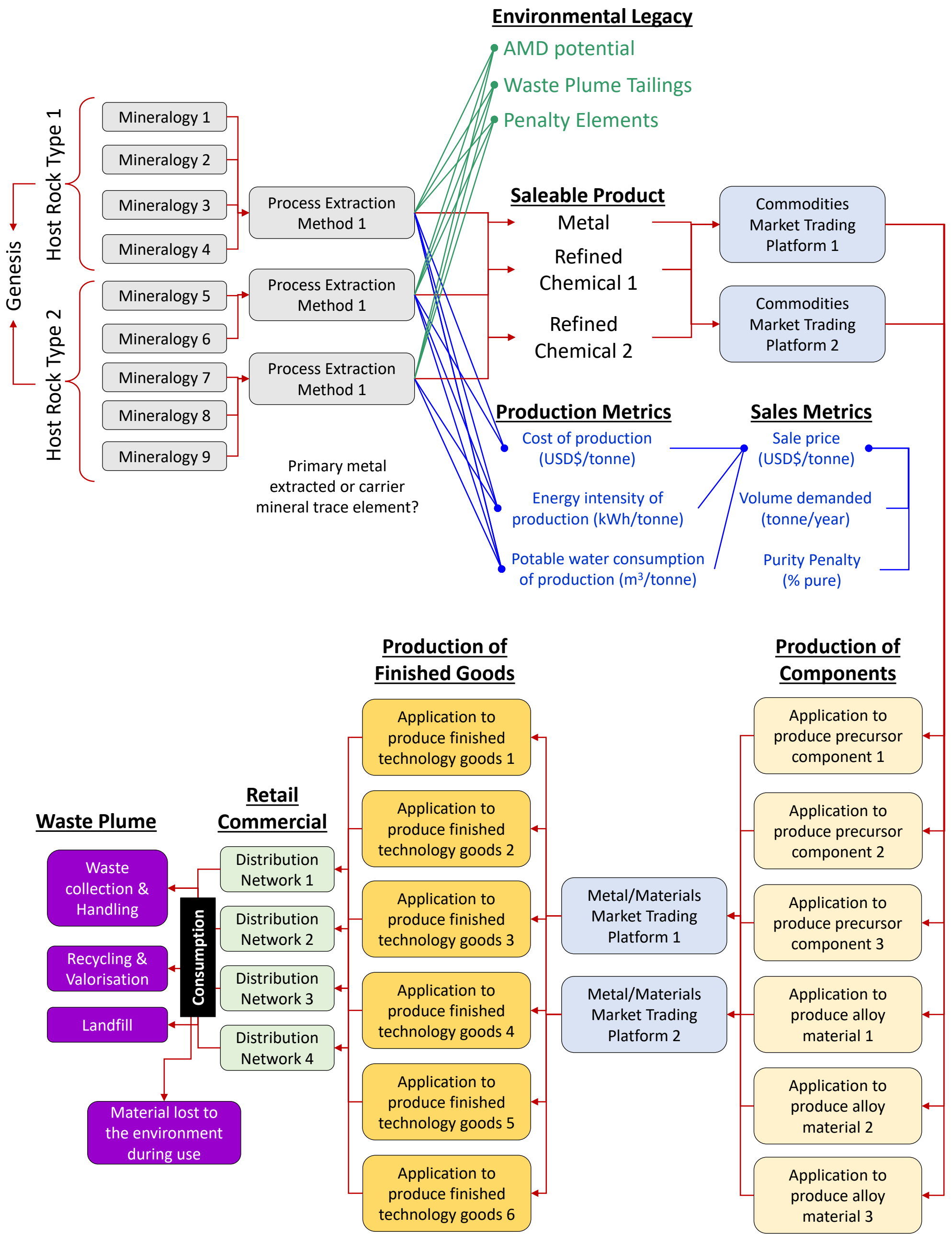
Digitalizing the circular economy

System simulation

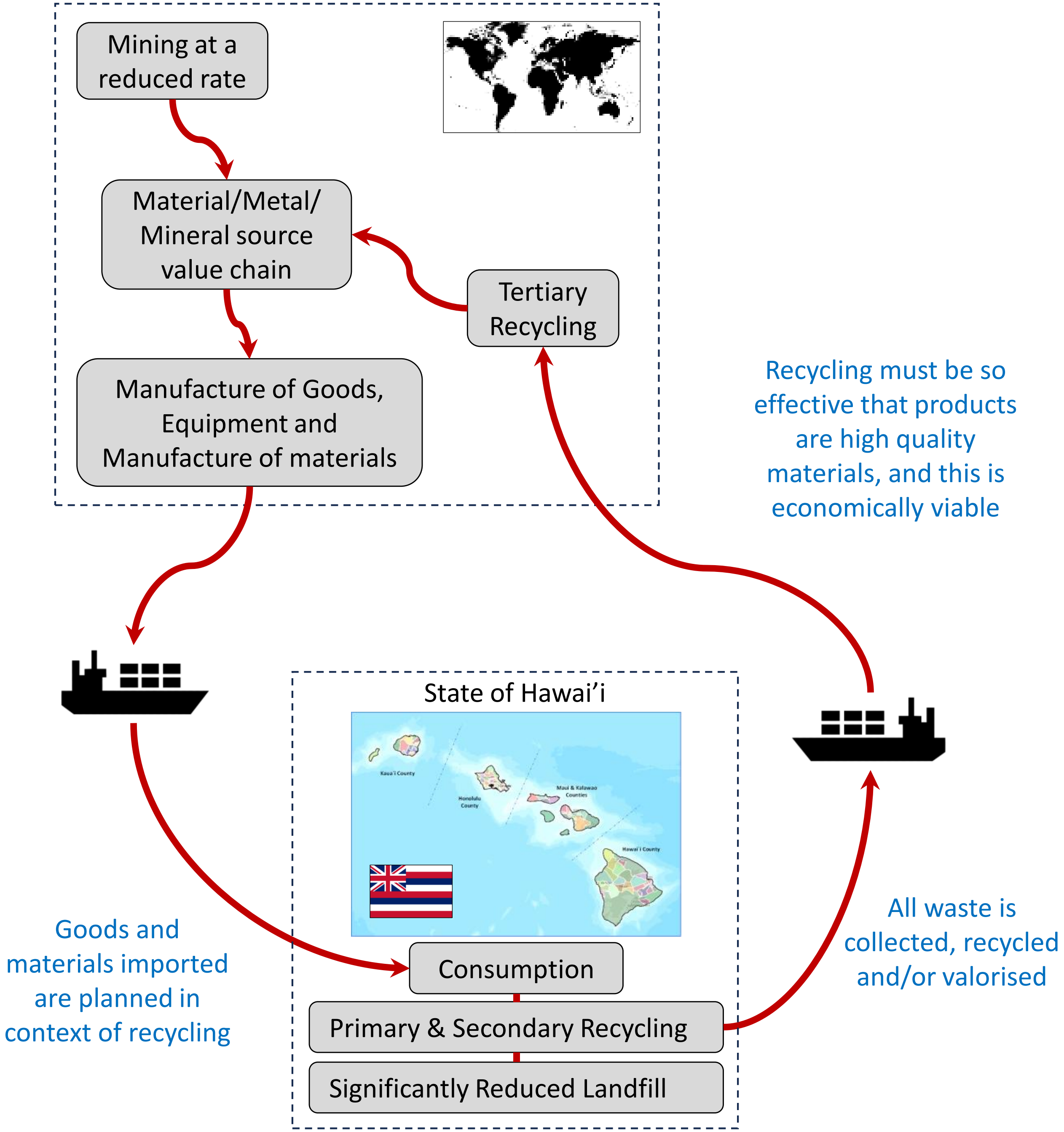




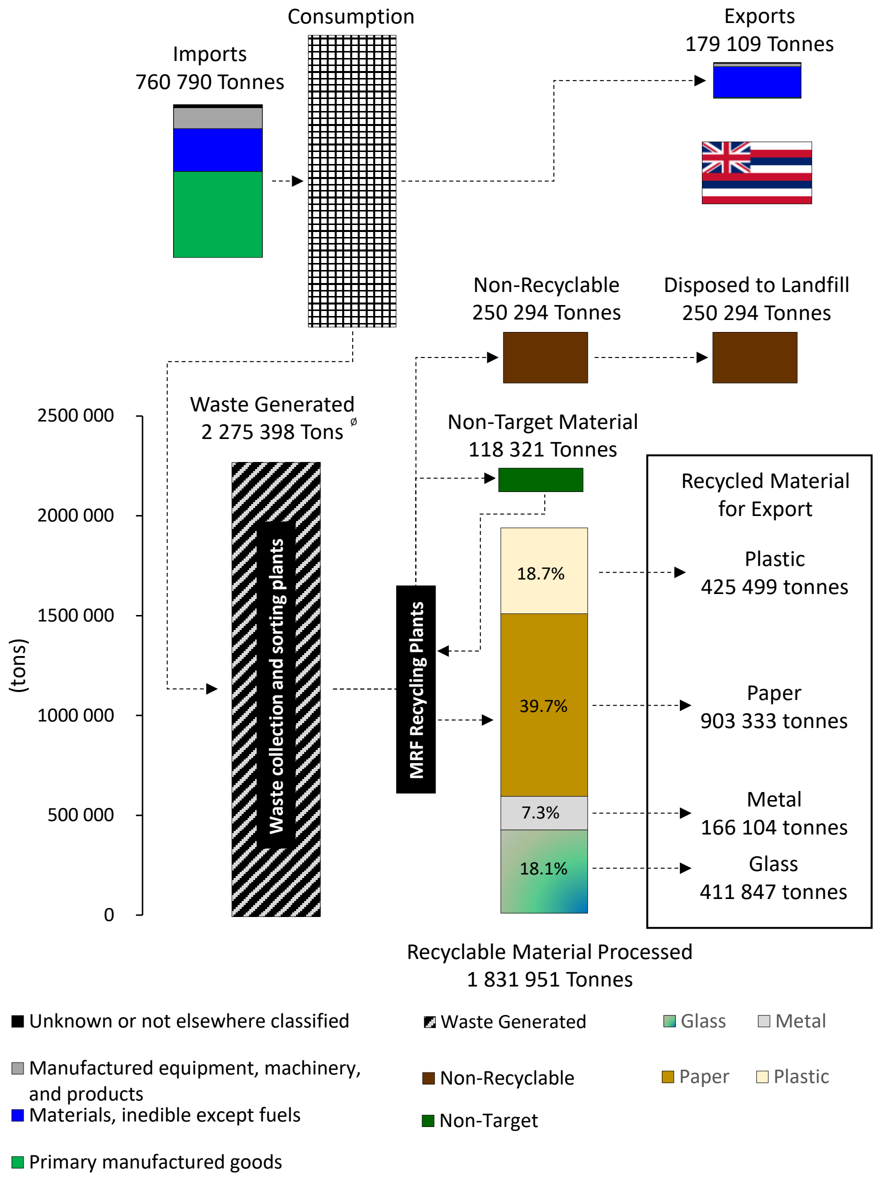
Exploration, mining, smelting & refining (mostly)
Copper
Aluminium
Steel
Plastics
Lithium
Cobalt
Nickel
Manganese
Graphite
Zinc
Zirconium
Germanium
Sodium
Battery Chemistry
Manufacture
Cathode
Anode
Electrolyte
Casing
Battery
Application
Renewable energy buffer wind turbines
Portable energy storage
Stationary energy storage
Power Tools
Tablets
Laptops
SMART Phones
Electric Vehicle Passenger cars
Electric Vehicle Buses
Electric Vehicle Forklifts
Electric Vehicle Autobicycles
Waste handling
Manufacture
Recycling



Genesis
Host Rock Type 1
Host Rock Type 2
Mineralogy 1
Mineralogy 2
Mineralogy 3
Mineralogy 4
Mineralogy 5
Mineralogy 6
Mineralogy 7
Mineralogy 8
Mineralogy 9
Process Extraction Method 1
Process Extraction Method 1
Process Extraction Method 1
Primary metal extracted or carrier mineral trace element?
Environmental Legacy
AMD potential
Waste Plume Tailings
Penalty Elements
Saleable Product
Metal
Refined Chemical 1
Refined Chemical 2
Commodities Market Trading Platform 1
Commodities Market Trading Platform 2
Production Metrics
Cost of production (USD$/tonne)
Energy intensity of production (kWh/tonne)
Potable water consumption of production (m³/tonne)
Sales Metrics
Sale price (USD$/tonne)
Volume demanded (tonne/year)
Purity Penalty (% pure)
Production of Components
Application to produce precursor component 1
Application to produce precursor component 2
Application to produce precursor component 3
Application to produce alloy material 1
Application to produce alloy material 2
Application to produce alloy material 3
Metal/Materials Market Trading Platform 1
Metal/Materials Market Trading Platform 2
Production of Finished Goods
Application to produce finished technology goods 1
Application to produce finished technology goods 2
Application to produce finished technology goods 3
Application to produce finished technology goods 4
Application to produce finished technology goods 5
Application to produce finished technology goods 6
Retail Commercial
Distribution Network 1
Distribution Network 2
Distribution Network 3
Distribution Network 4
Consumption
Waste Plume
Waste collection & Handling
Recycling & Valorisation
Landfill
Material lost to the environment during use


Mining at a reduced rate
Material/Metal/ Mineral source value chain
Manufacture of Goods, Equipment and Manufacture of materials
Tertiary Recycling
Recycling must be so effective that products are high quality materials, and this is economically viable
State of Hawai'i
Consumption
Primary & Secondary Recycling
Significantly Reduced Landfill
Goods and materials imported are planned in context of recycling
All waste is collected, recycled and/or valorised

Mass Flows Scenario HG Circular Economy in State of Hawai'i
(based on 2019 footprint)



ø This does not include construction waste

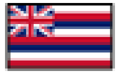
Appendix Mu (µ) shows a more complete discussion of the pyrolysis of rubber tyres, and the calculation path for Table 207.

Table 207. **POTENTIAL ANNUAL DIESEL FUEL PRODUCTION VIA THE PYROLYSIS OF EOL TYRES IN THE STATE OF HAWAIʻI**

Number of EoL tyres produced a year State of Hawai'i *	Mass of each EoL tyre *	Annual mass of EoL Tyre rubber to recycle	Quantity of pyrolysis oil produced ♣	Quanity of diesel fuel produced ♥		
(number)	(kg)	(tonnes)	(tonnes)	(tonnes)	(million liters) ♠	(gallons)
750,000	8	6,000	3,000	1,836	2.21	582,957

* Assumed to be all passenger car tyres for this exercise
♣ Where 1000 kg of rubber tyres produces 500 kg of oil with pyrolysis
♥ Where 1000 kg of pyrolysis oil produces 612 kg of diesel fuel
♠ Diesel for automotive use is around 832 kg/m3, or 0.832 kg/liter

Table 208. **ANNUAL PRODUCTION OF SYNGAS FROM SEWAGE IN STATE OF HAWAI'I**
(summation of Tables 241 to 243)

 Human sewage produced in State of Hawai'i 2019 *			Annual dry sludge solids per capita	Thermal heat required to process sewage with pyrolysis ♣	Production of useful syngas ®
(millions of gallons)	(millions of liters)	(m^3)	(kg)	(MWh thermal)	(tonne)
40,179	152,094	1.52E+08	3.04E+07	6,780.9	2,646

* Appendix D, Table D4

♠ Wastewater treatment typically results in the production of about 0.1 to 0.3 kg (assume 0.2 kg) of dry sludge solids per cubic meter of wastewater treated (Alth et al. 1992).
♣ Calculation described in full in Appenidx Iota (i)
® Assuming 8.7% of the feedstock dried human sewage solids mass is converted into commercially useful syngas. Appendix Kappa (κ)

To produce 1 tonne of syngas, the annual sewage generated by 443 people (57,544 m^3 of wastewater containing 11.45 tonnes of dried sludge) is to be collected. This approach not only provides an energy source from a waste stream, but it also provides a much more logistically simple way to deal with a waste stream. But, if it's handled inappropriately, it has the capacity to seriously damage public health. This is one of those rare win/win solutions.

Appendix Kappa (κ) shows a more complete discussion of the pyrolysis of human sewage as an energy source.

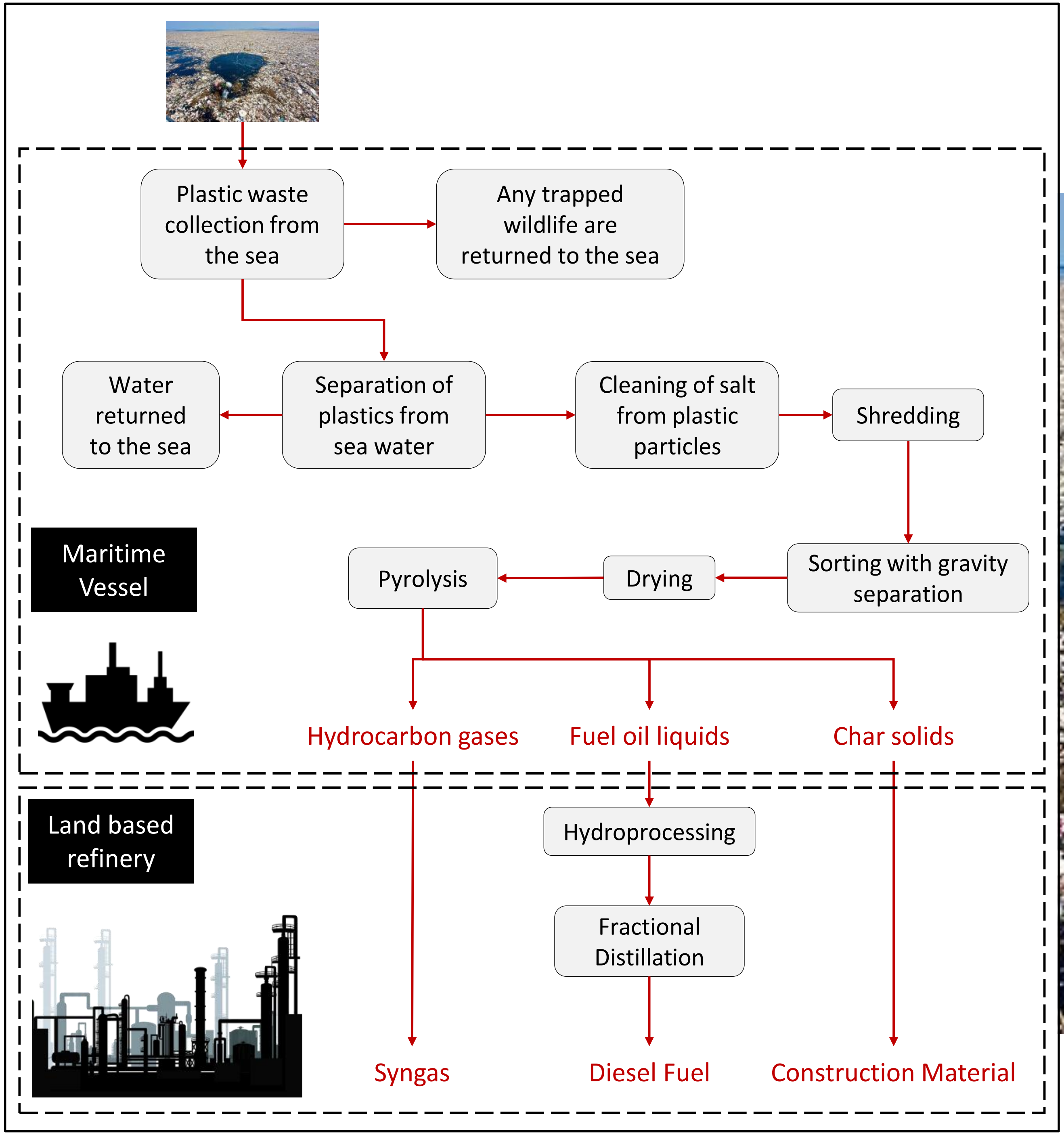
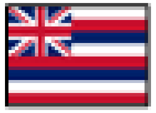

Plastic waste collection from the sea
Any trapped wildlife are returned to the sea
Water returned to the sea
Separation of plastics from sea water
Cleaning of salt from plastic particles
Shredding
Maritime Vessel
Pyrolysis
Drying
Sorting with gravity separation
Hydrocarbon gases
Fuel oil liquids
Char solids
Land based refinery
Hydroprocessing
Fractional Distillation
Syngas
Diesel Fuel
Construction Material

Table 209. **DAILY PRODUCTION OF PYROLYSIS OUTPUTS FROM PLASTIC WASTE COLLECTION**

 Daily plastic ocean waste recovered Put through pyrolysis plant	Solid char produced	Gaseous Products (Syngas)	Pyrolysis oil produced	Diesel fuel produced		
(tonne)	(tonne)	(tonne)	(tonne)	(tonne)	(gallons)	(liters)
40	8	4	28.0	17.696	5,447	20,616

If it is assumed that this vessel was able to harvest 40 tonnes of plastic waste per day (to feed four 10 tonne pyrolysis plants), and the mass of plastic in the Great Garbage Patch pacific gyre was considered to be 87,000 tonnes, then this one ship could completely clear that gyre in 6.2 years (assuming 350 days a year of production).

Conventional Circular Economy (Scenario HG)

Small capacity MRF recycling facilities	12	Existing waste streams domestic & industrial 42 plants
Medium capacity MRF recycling facilities	13	
Large capacity MRF recycling facilities	13	
Extra large capacity MRF recycling facilities	4	
Small capacity MRF recycling facilities	2	Recycling EoL ICE, EV's, solar panels, wind turbines & batteries
Medium capacity MRF recycling facilities	1	
Large capacity MRF recycling facilities	2	
Extra large capacity MRF recycling facilities	4	
Small pyrolysis plant to recycle EoL tyres	1	Recycle EoL vehicle tyres, and human sewage into energy fuel
Small pyrolysis plant to process human sewage	1	
Total	**53**	

Green Transition Transport (Scenario HE-1)

Electric Vehicles (EV), various classes	1.27 million (60.4 GWh battery capacity)
Electric Vehicle charging stations	1.1 million EV charging stations (privately owned, and publically assessible)
Hydrogen fuel cell (H_2-Cell) land transport heavy vehicles	7,801
Hydrogen fuel (H_2-Cell) 17% of maritime vessels	1,928
Ammonia ICE 46% of maritime vessels	5,218
Biofuel ICE 38% of maritime vessels	4,197
Annual hydrogen production & storage capacity	164 315 tonnes
Annual ammonia production & storage capacity	20 413 tonnes
Annual ethanol biofuel production & storage capacity (37% of domestic maritime gasoline)	511 232 gallons, 1.7 miles^2 area of arable land
Annual aviation bio fuel production & storage capacity (domestic maritime and domestic aviation)	271 million gallons, 904 miles^2 area of arable land
Annual biodiesel production & storage capacity (37% of domestic maritime diesel)	1.28 million gallons, 33.8 miles^2 area of arable land

Green Transition Electricity Generation (Scenario HE-1)

Solar PV installed capacity	12.51 GW, or 27.8 million 450 watt capacity solar PV panels
Wind trubine installed capacity	1.8 GW, or 275 turbines of 6.6 MW capacity
Stationary power storage intsalled capacity (assumed 28 days storage)	627.2 GW, or 3 390 Kapolei Energy Storage sites of 185 MW/565 MWh capacity
Combined Heat & Power (CHP) biowaste to energy installed capacity	605 MW, 2.5 million m^3 of wood biomass, sustainably harvested annually from 1 608 miles^2 of mature forest land
Hydroelectric installed capacity	112 MW

Stationary power storage

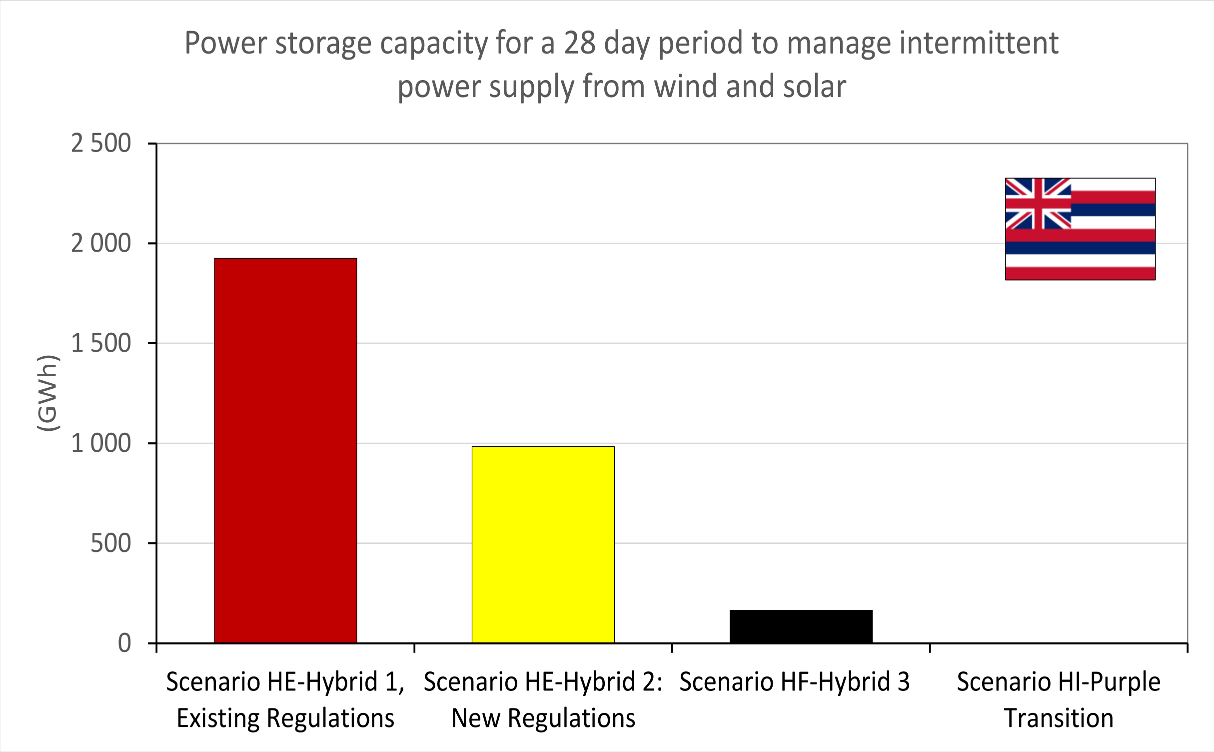


Figure 197. **ELECTRICITY TO BE STORED AND DELIVERED TO THE POWER GRID WHEN THERE IS A SHORTFALL IN SUPPLY FROM WIND AND SOLAR PV SYSTEMS**

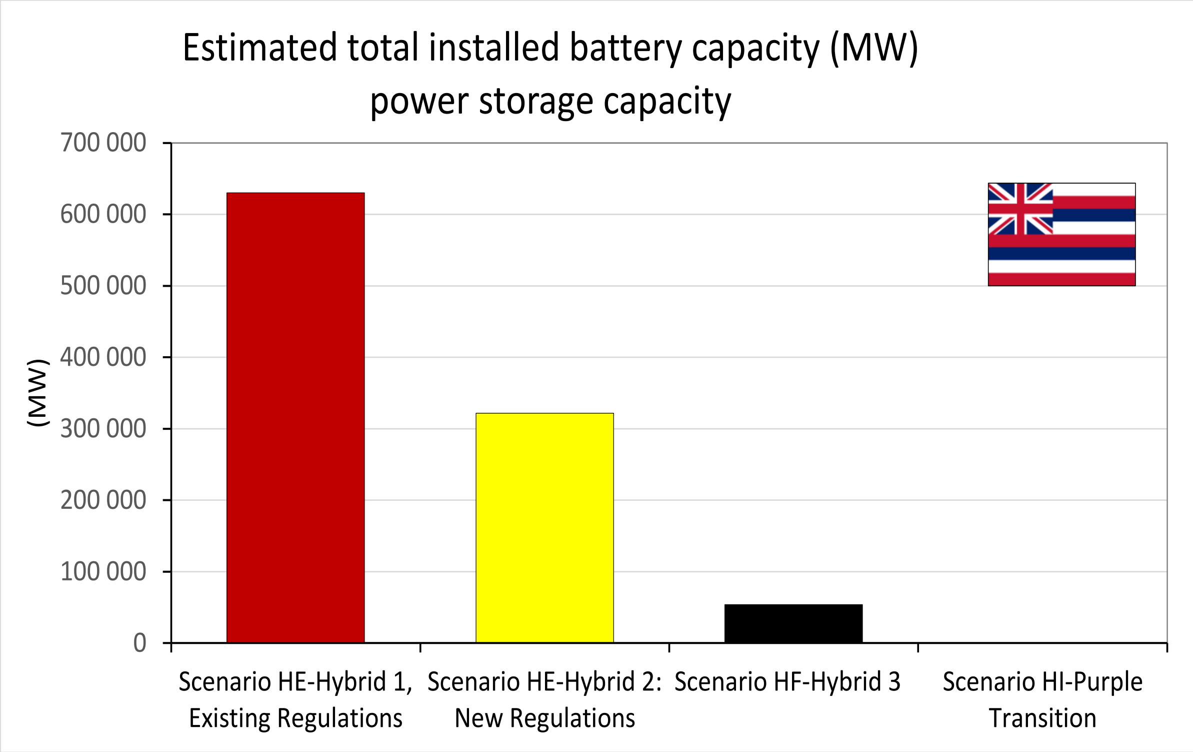


Figure 198. **INSTALLED BATTERY BANK CAPACITY NEEDED TO MEET POWER STORAGE REQUIREMENTS**

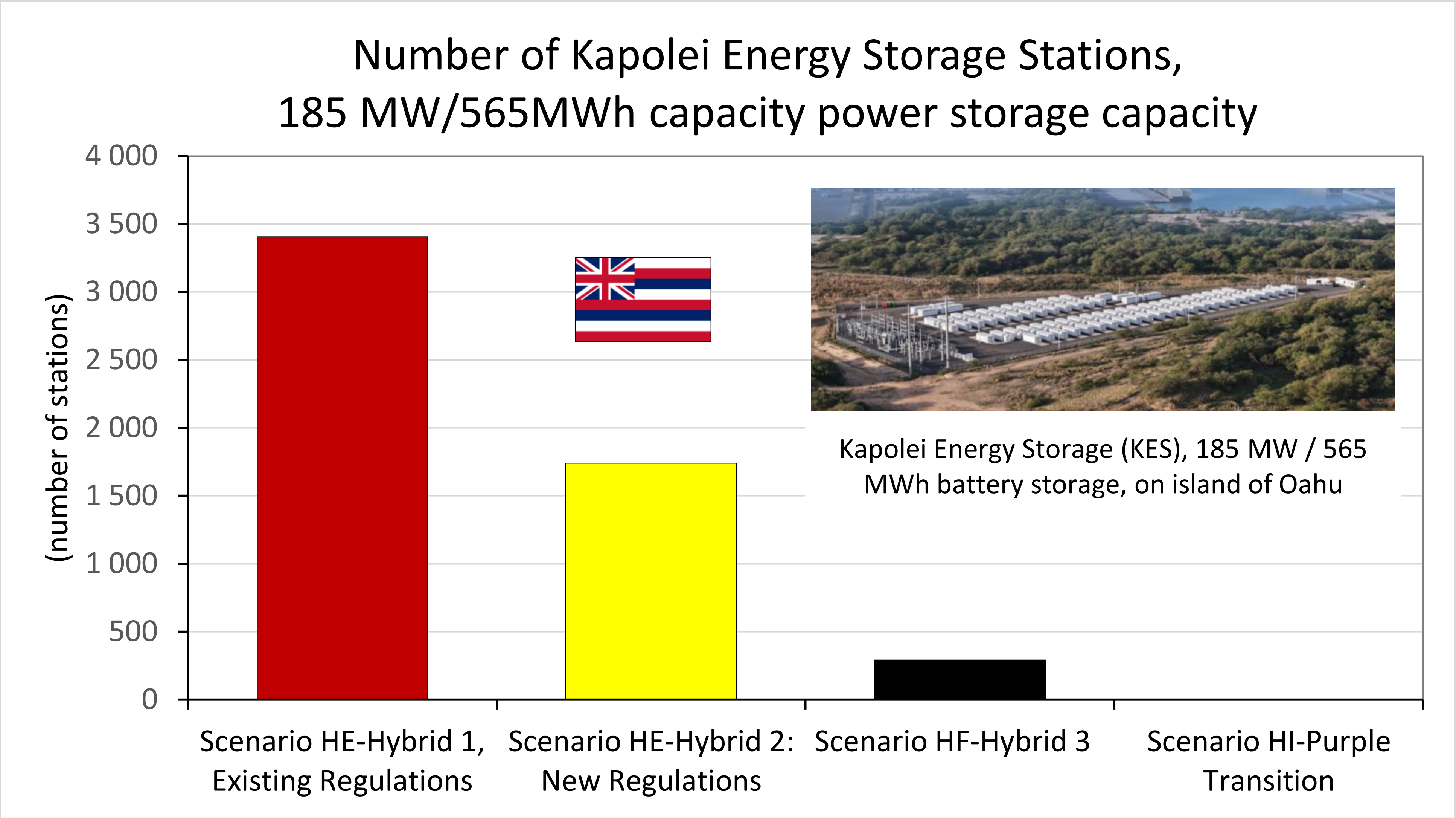
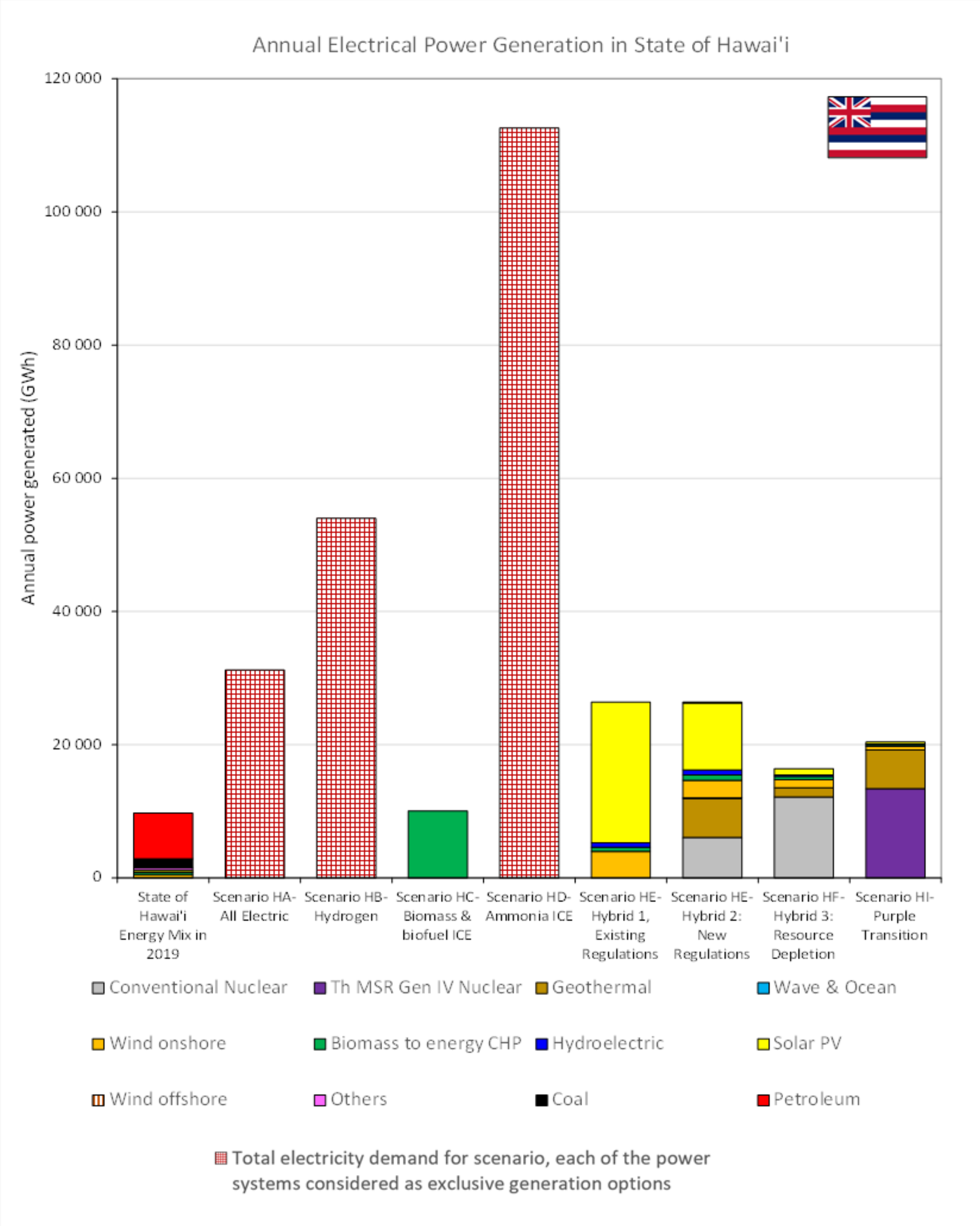


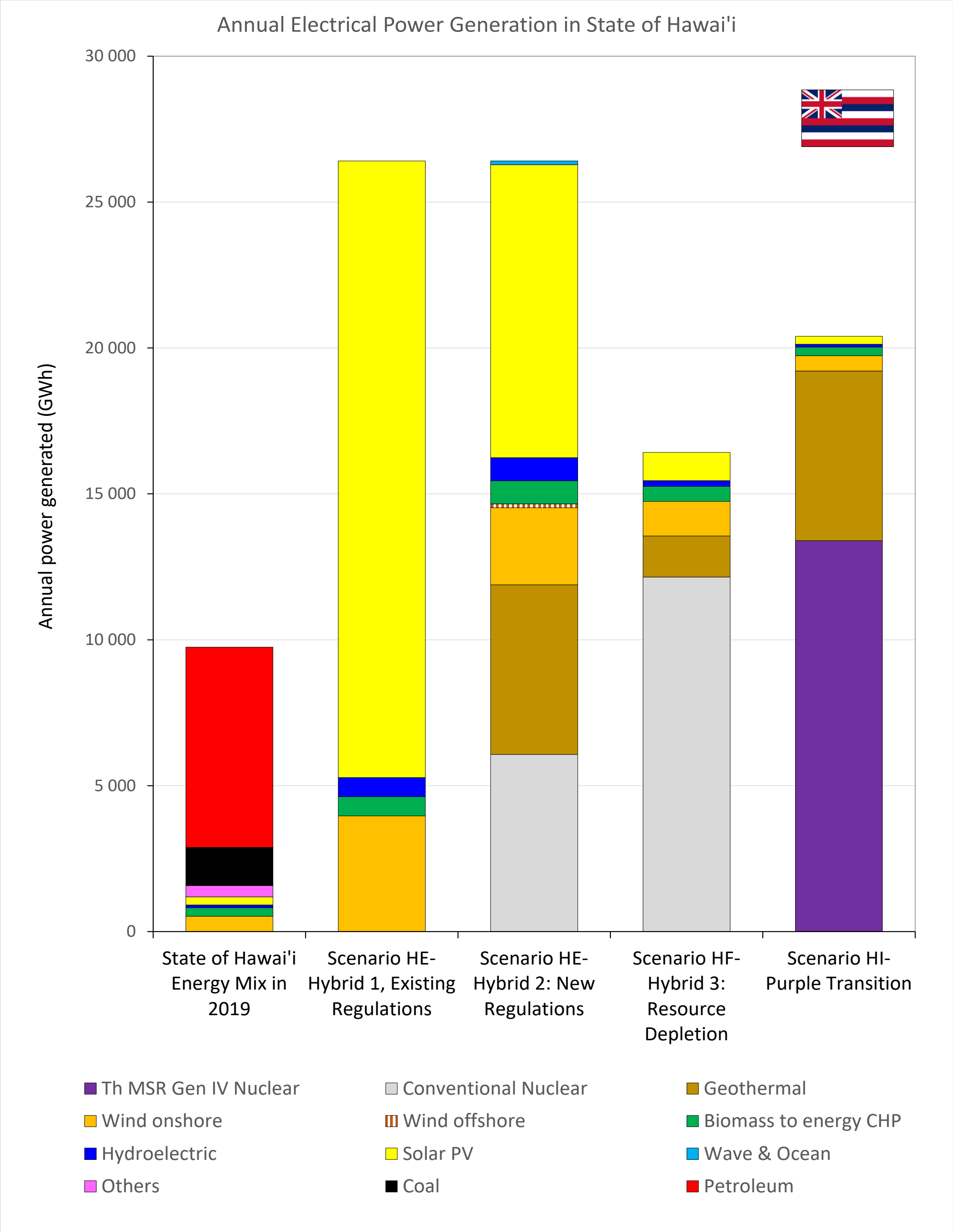
Figure 199. **THE NUMBER OF 185 MW/565 MWH STATION POWER STORAGE STATIONS (EXAMPLE: KAPOLEI ENERGY STORAGE) REQUIRED TO MANAGE INTERMITTENT ELECTRICITY GENERATION FROM WIND AND SOLAR PV SYSTEMS.**
Kapolei on the island of Oahu (Source: Kapolei Energy Storage)

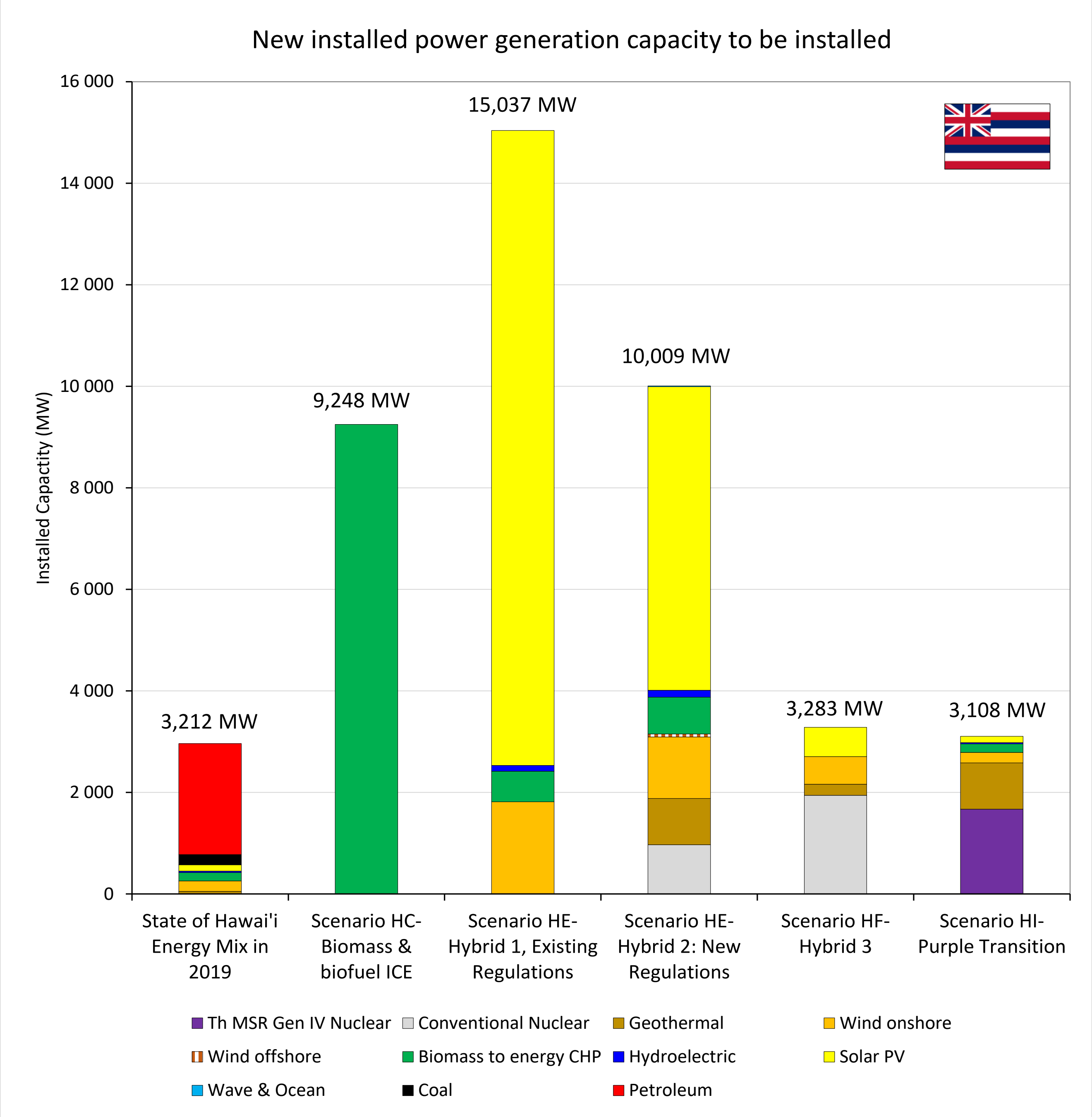
Scenario HH: Regenerative Permaculture

- This scenario was developed to examine the question of what would be needed if the entire state of Hawai’i sourced its food from completely organic sources
- All petrochemical fertilizers, herbicides, and pesticides were assumed to be 100% phased out and replaced with organic systems
- Paradigms to be examined were regenerative agriculture, permaculture, and food forest agriculture
- A model was developed to assess what kind of arable land footprint, a community of 200 people would require in this context
- This was then projected onto a map of the Hawaiian island chain in context of the available arable land of all kinds.



Annual Electrical Power Generation in State of Hawai'i
Annual power generated (GWh)
120 000
100 000
80 000
60 000
40 000
20 000
0
State of Hawai'i Energy Mix in 2019
Scenario HA- All Electric
Scenario HB- Hydrogen
Scenario HC- Biomass & biofuel ICE
Scenario HD- Ammonia ICE
Scenario HE- Hybrid 1, Existing Regulations
Scenario HE- Hybrid 2: New Regulations
Scenario HF- Hybrid 3: Resource Depletion
Scenario HI- Purple Transition
Conventional Nuclear
Th MSR Gen IV Nuclear
Geothermal
Wave & Ocean
Wind onshore
Biomass to energy CHP
Hydroelectric
Solar PV
Wind offshore
Others
Coal
Petroleum
Total electricity demand for scenario, each of the power systems considered as exclusive generation options


Annual Electrical Power Generation in State of Hawai'i
Annual power generated (GWh)
30 000
25 000
20 000
15 000
10 000
5 000
0
State of Hawai'i Energy Mix in 2019
Scenario HE-Hybrid 1, Existing Regulations
Scenario HE-Hybrid 2: New Regulations
Scenario HF-Hybrid 3: Resource Depletion
Scenario HI-Purple Transition
Th MSR Gen IV Nuclear
Conventional Nuclear
Geothermal
Wind onshore
Wind offshore
Biomass to energy CHP
Hydroelectric
Solar PV
Wave & Ocean
Others
Coal
Petroleum


New installed power generation capacity to be installed
Installed Capacity (MW)
16 000
14 000
12 000
10 000
8 000
6 000
4 000
2 000
0
3,212 MW
9,248 MW
15,037 MW
10,009 MW
3,283 MW
3,108 MW
State of Hawai'i Energy Mix in 2019
Scenario HC-Biomass & biofuel ICE
Scenario HE-Hybrid 1, Existing Regulations
Scenario HE-Hybrid 2: New Regulations
Scenario HF-Hybrid 3
Scenario HI-Purple Transition
Th MSR Gen IV Nuclear
Conventional Nuclear
Geothermal
Wind onshore
Wind offshore
Biomass to energy CHP
Hydroelectric
Solar PV
Wave & Ocean
Coal
Petroleum

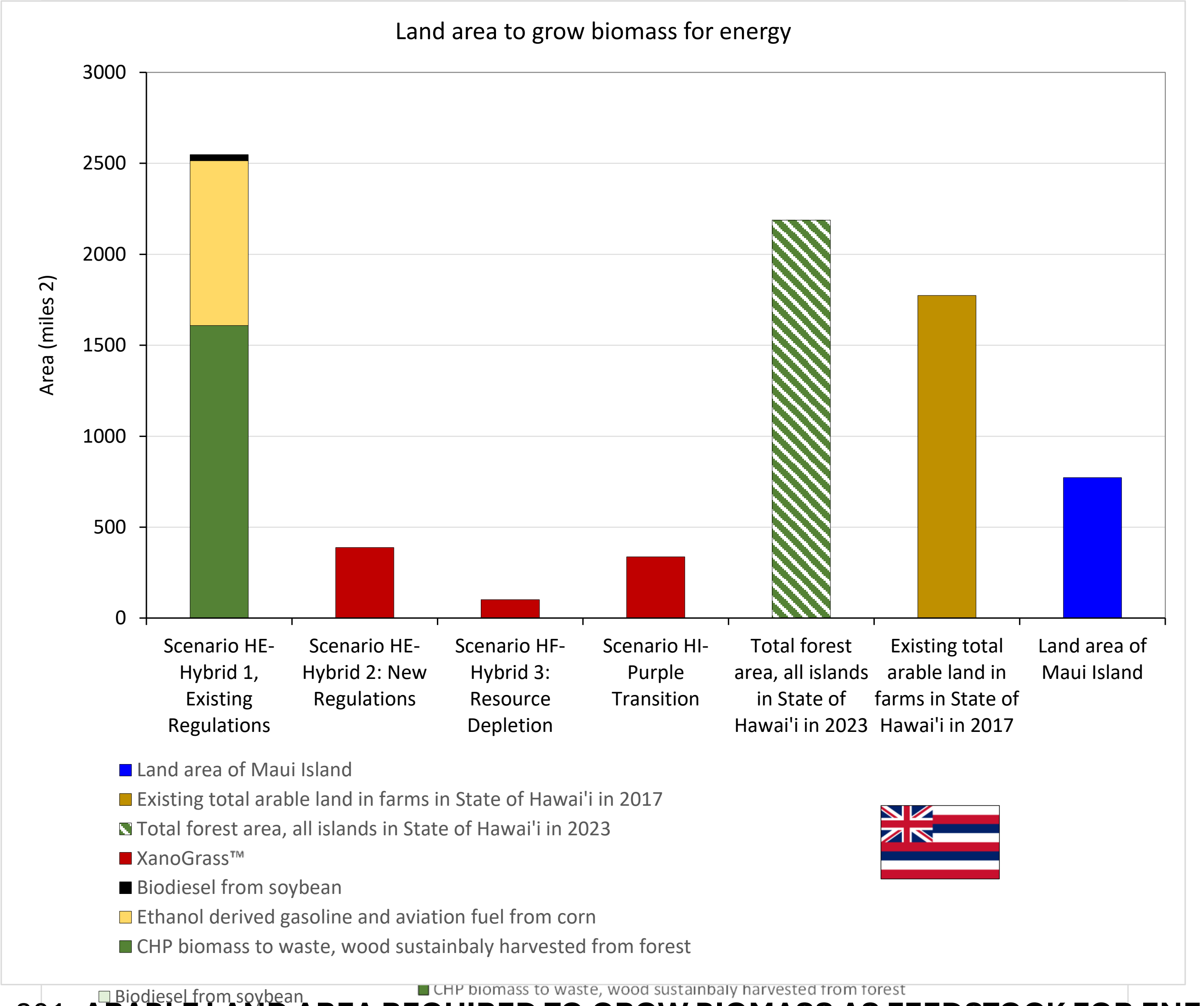
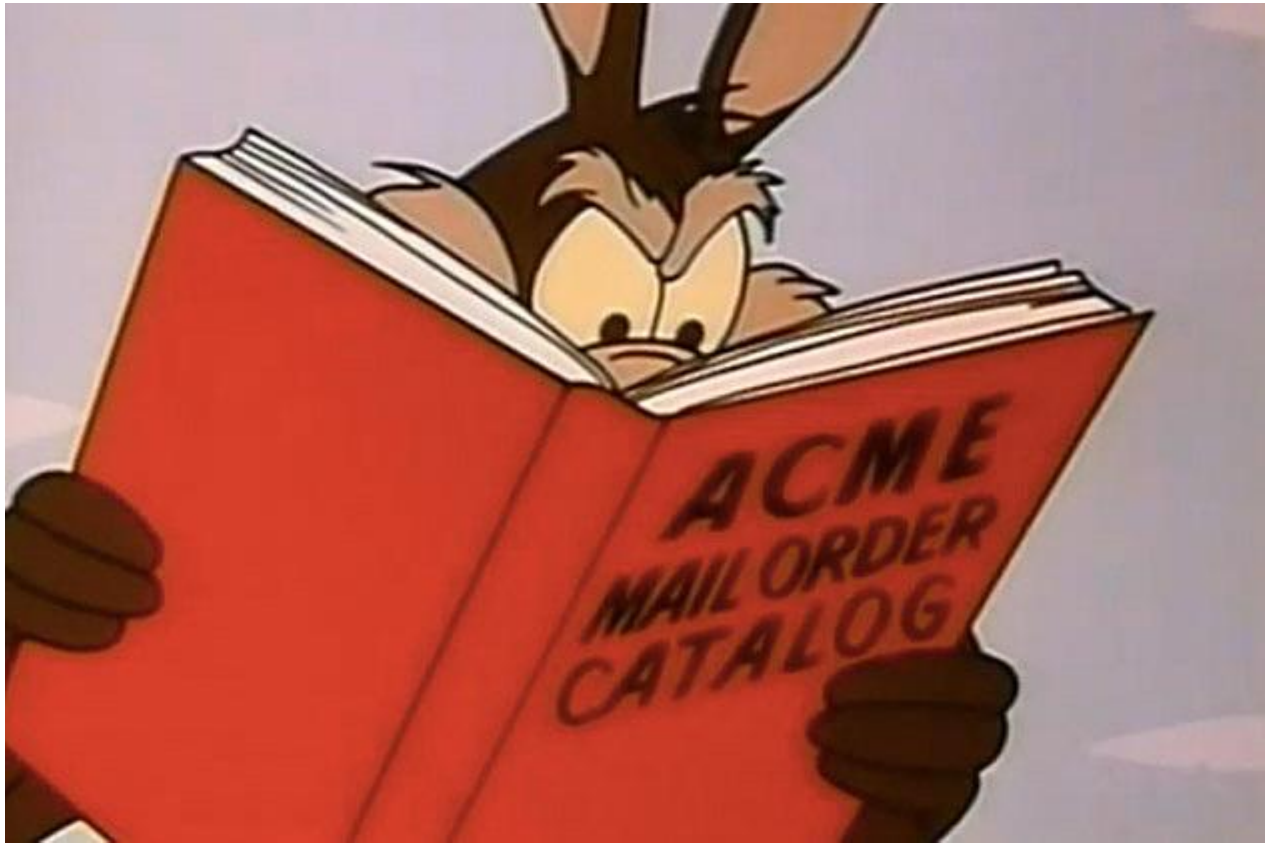


Figure 201. **ARABLE LAND AREA REQUIRED TO GROW BIOMASS AS FEEDSTOCK FOR ENERGY IN EACH RELEVANT SCENARIO FOR THE STATE OF HAWAI'I, NOT INCLUDING SCENARIO HC**

Figure 200. **ARABLE LAND AREA REQUIRED TO GROW BIOMASS AS FEEDSTOCK FOR ENERGY IN EACH RELEVANT SCENARIO FOR THE STATE OF HAWAI'I, INCLUDING SCENARIO HC**

Conventional thinking won’t work



- All conventional strategies to phase out fossil fuels have logistical scaleup bottlenecks that make them probably unviable
- When the orthodox conventional fails, turn to the unorthodox and the unconventional, or accept failure

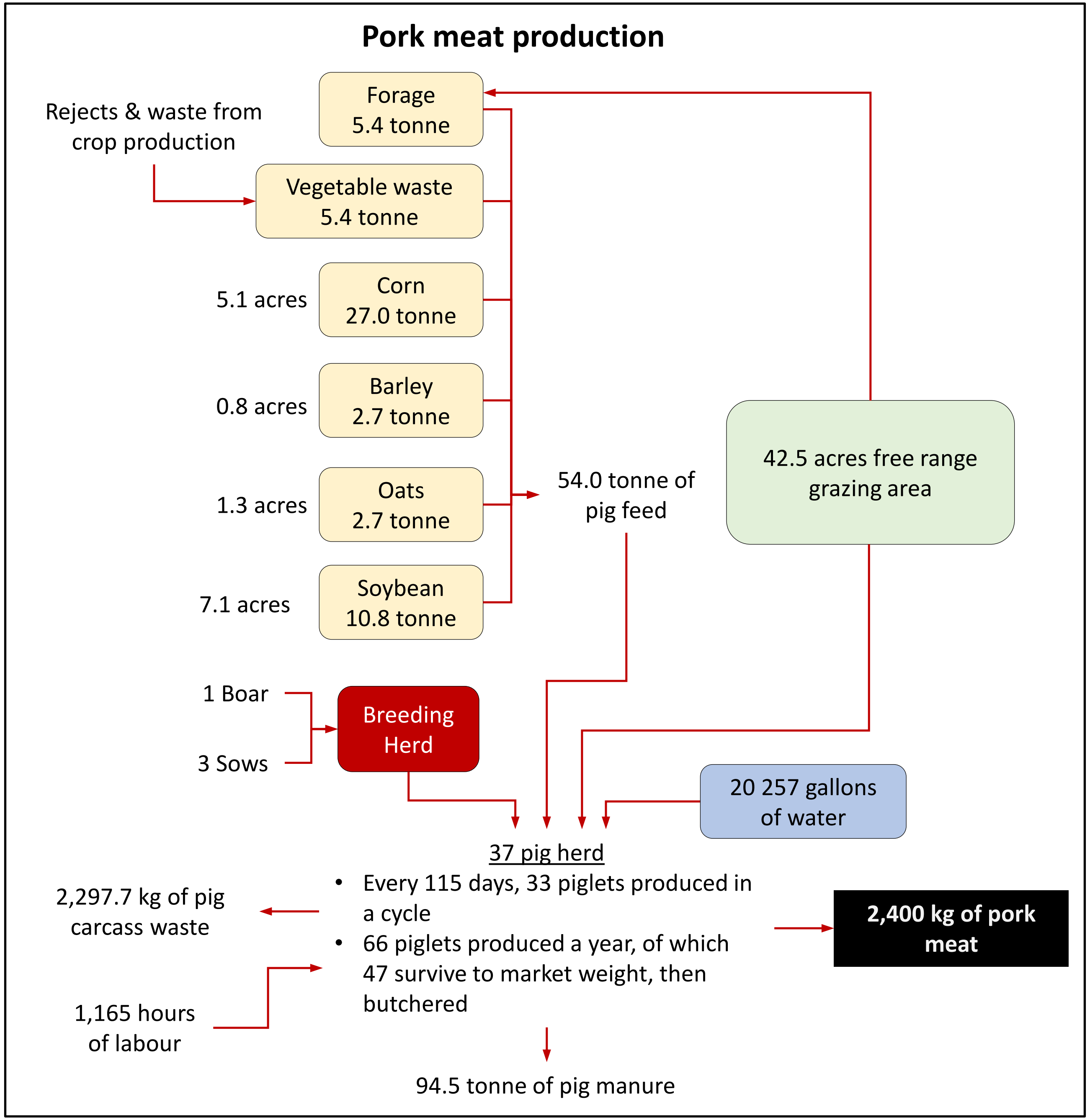
Scenario HH – Regenerative Permaculture

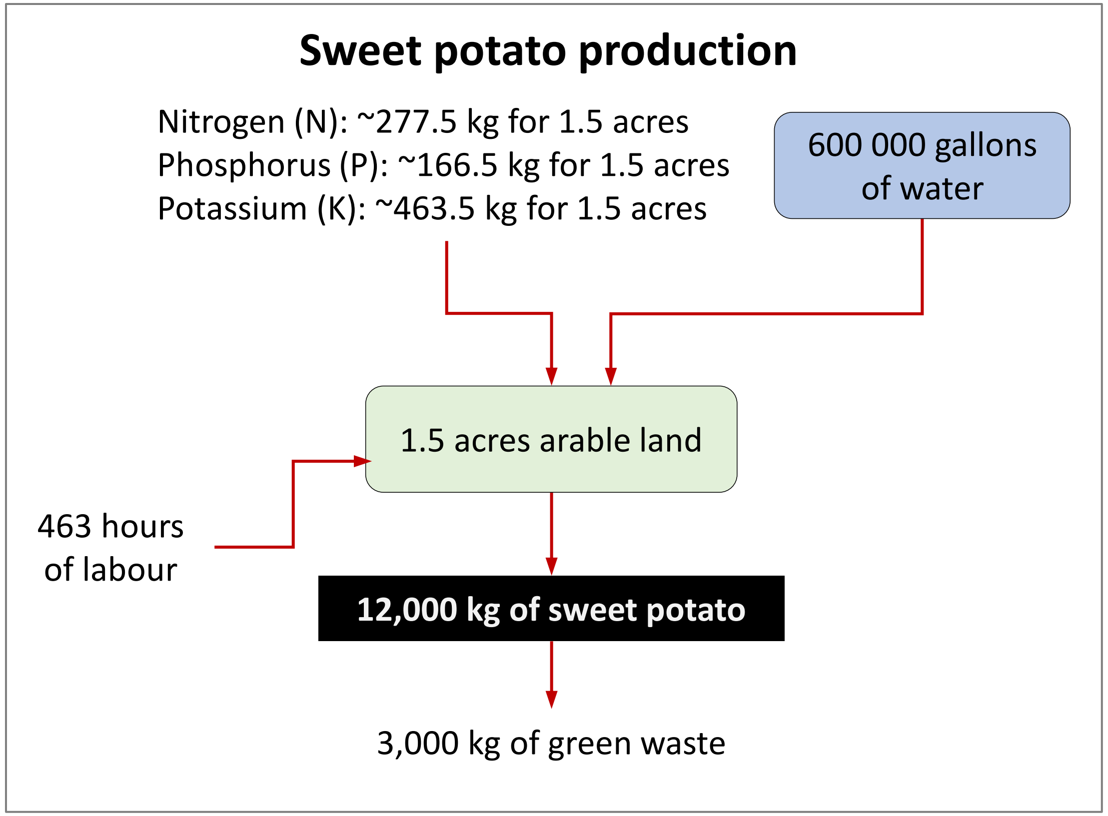
Table 227. **PROPOSED NUTRITIONAL ANNUAL DIET FOR A SINGLE PERSON AND FOR 200 PEOPLE** in Scenario HH
(Source: Ward & Poly 2016, Hoffmann 2016, Hawaii Department of Agriculture 2020, Fielding 2015, HDOA 2024, Schoenfeld & Aragon 2018)

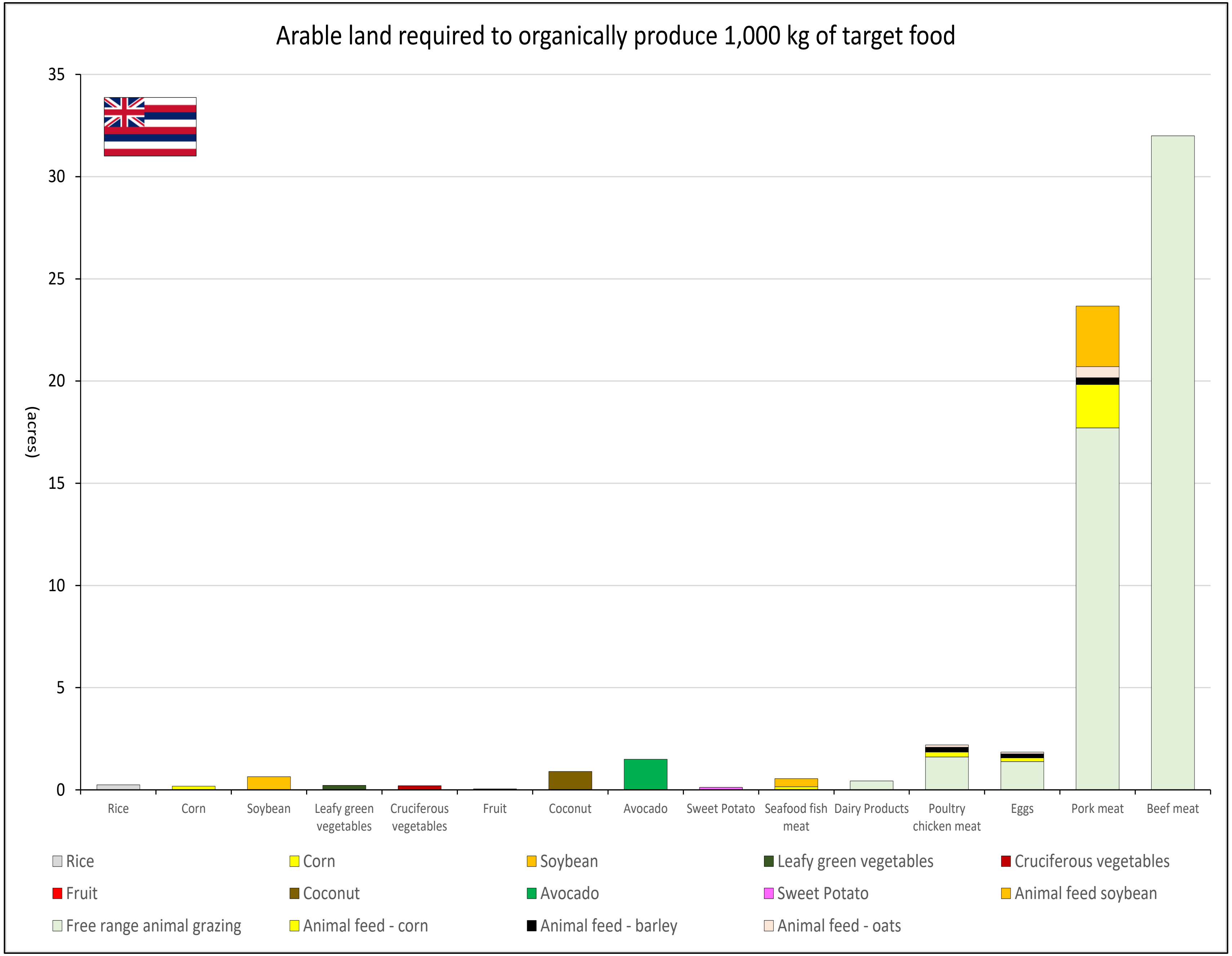
Food type	Proposed nutritional daily diet per capita for Scenario HH		Proposed nutritional annual diet per capita for Scenario HH		Proposed annual diet for 200 people in Scenario HH
	(g/day)	(estimated calories/day)	(kg/year)	(estimated calories/year)	(kg)
Rice	219.2	789	80	288,000	16,000
Corn	82.2	82	30	30,000	6,000
Fruits & Berries	68.5	103	25	37,500	5,000
Leafy Green vegetables	123.3	31	45	11,250	9,000
Cruciferous Vegetables	95.9	24	35	8,750	7,000
Sweet Potatoes	164.4	141	60	51,480	12,000
Coconuts	54.8	60	20	22,000	4,000
Avocardo	43.8	104	16	38,000	3,200
Pork	32.9	82	12	30,000	2,400
Poultry	82.2	196	30	71,700	6,000
Eggs	82.2	148	30	54,000	6,000
Seafood and fish	68.5	49	25	18,000	5,000
Dairy	151.1	69	55.2	25148,4 *	17,264
Soybeans, Legumes, Nuts, and Seeds	42.5	306	15.5	111,600	2,000
Fats and oils	54.8	316	15	115,500	4,000
Total Mass	1,222.3	2,501	494	912,928	104,864

* includes milk and cheese made from milk

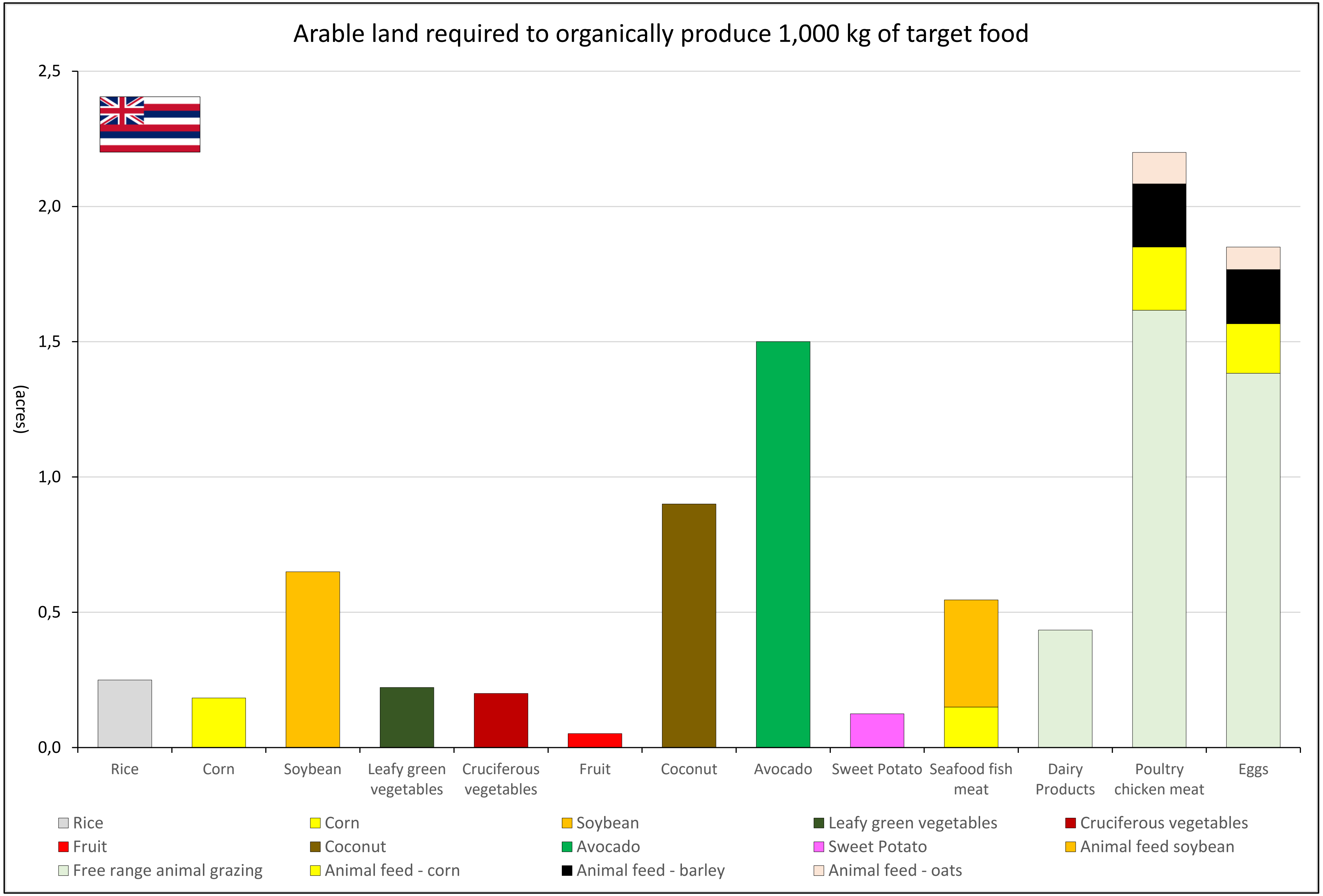
All food is grown locally, 100% organic without the use of petrochemical fertilizers or GMO tech


Pork meat production
Rejects & waste from crop production
Forage 5.4 tonne
Vegetable waste 5.4 tonne
5.1 acres
Corn 27.0 tonne
0.8 acres
Barley 2.7 tonne
1.3 acres
Oats 2.7 tonne
7.1 acres
Soybean 10.8 tonne
54.0 tonne of pig feed
42.5 acres free range grazing area
1 Boar
3 Sows
Breeding Herd
20 257 gallons of water
37 pig herd
• Every 115 days, 33 piglets produced in a cycle
• 66 piglets produced a year, of which 47 survive to market weight, then butchered
2,297.7 kg of pig carcass waste
2,400 kg of pork meat
1,165 hours of labour
94.5 tonne of pig manure

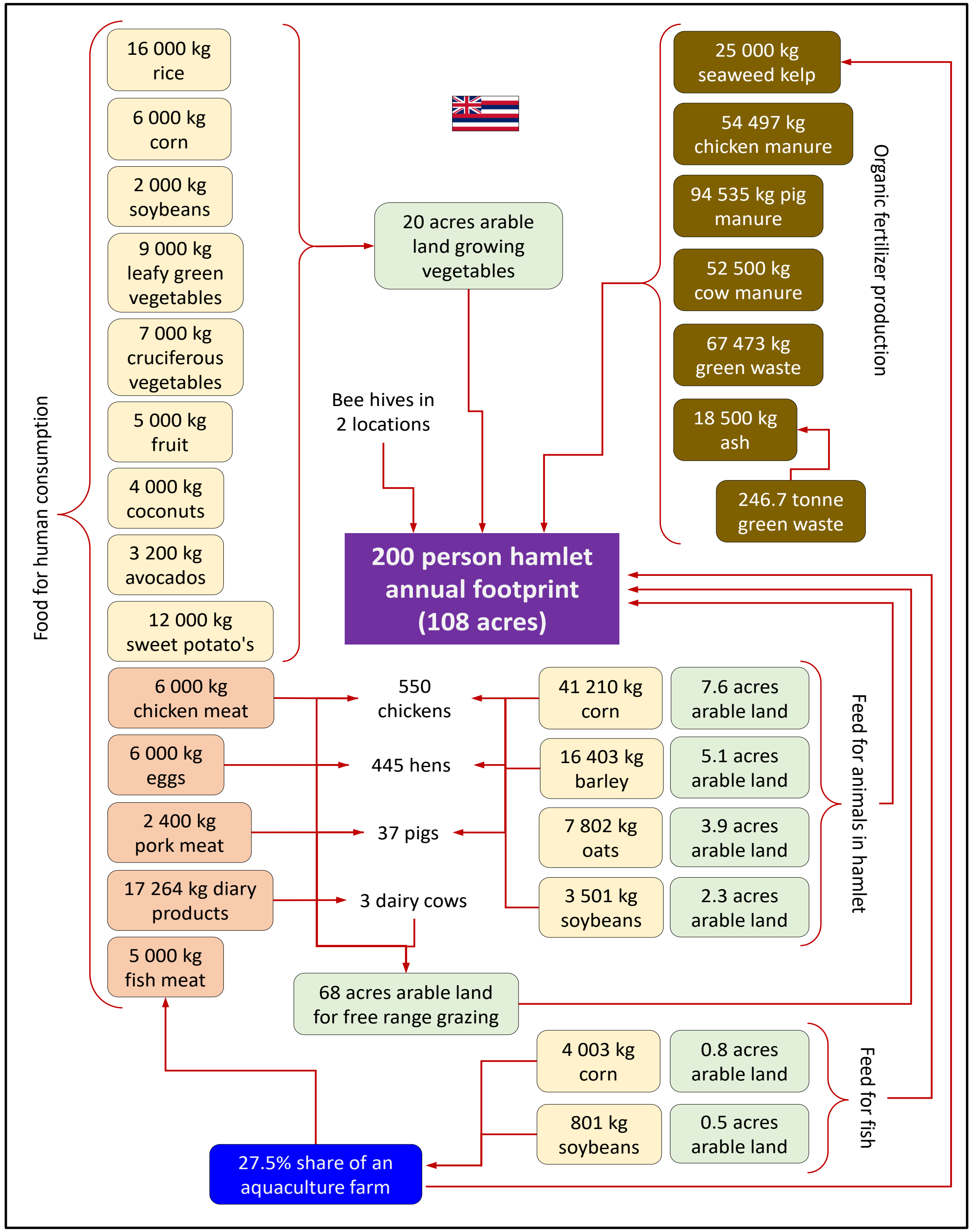

Sweet potato production
Nitrogen (N): ~277.5 kg for 1.5 acres
Phosphorus (P): ~166.5 kg for 1.5 acres
Potassium (K): ~463.5 kg for 1.5 acres
600 000 gallons of water
1.5 acres arable land
463 hours of labour
12,000 kg of sweet potato
3,000 kg of green waste



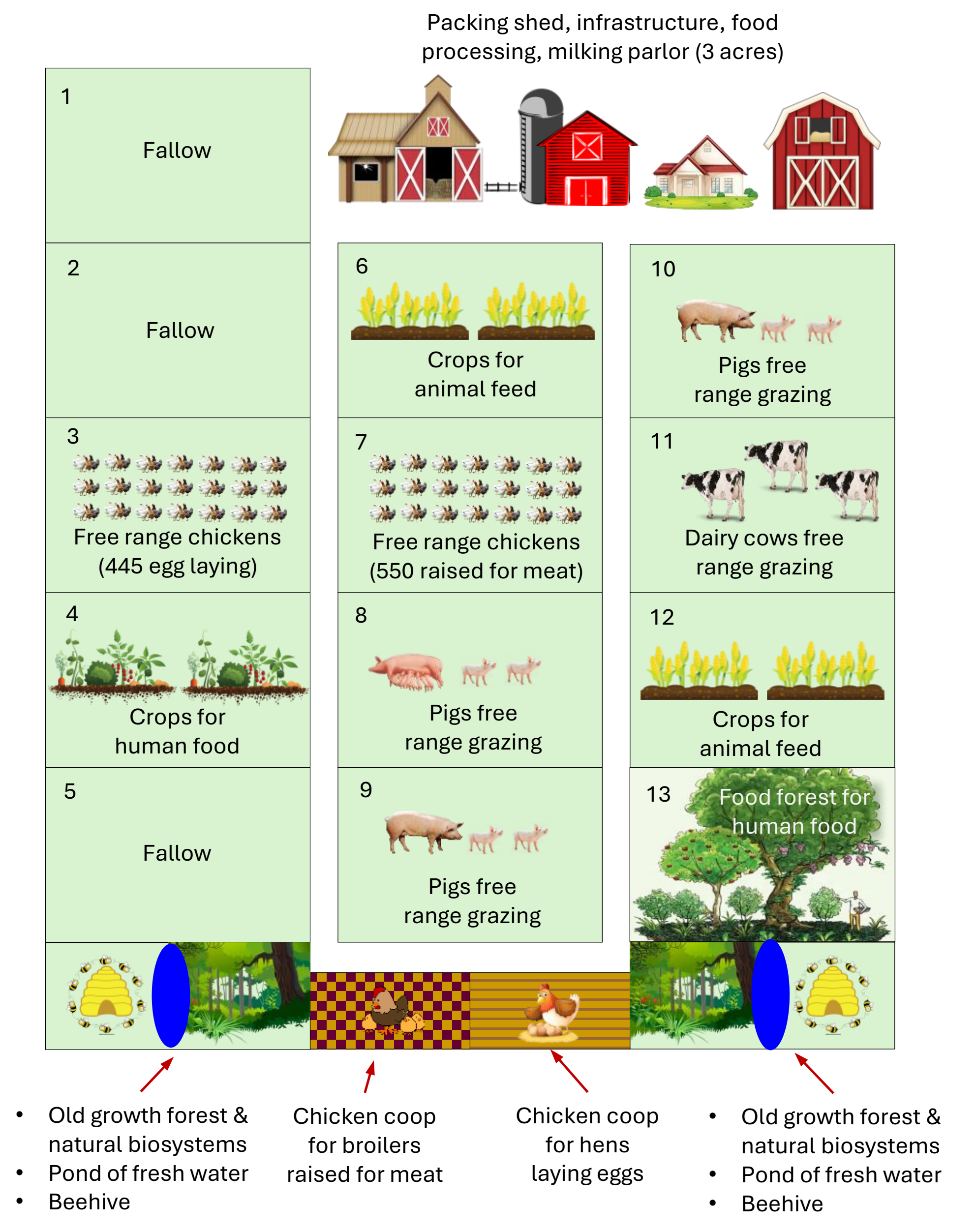
Arable land required to organically produce 1,000 kg of target food
35
30
25
20
15
10
5
0
(acres)
Rice
Corn
Soybean
Leafy green vegetables
Cruciferous vegetables
Fruit
Coconut
Avocado
Sweet Potato
Seafood fish meat
Dairy Products
Poultry chicken meat
Eggs
Pork meat
Beef meat
Rice
Corn
Soybean
Leafy green vegetables
Cruciferous vegetables
Fruit
Coconut
Avocado
Sweet Potato
Animal feed soybean
Free range animal grazing
Animal feed - corn
Animal feed - barley
Animal feed - oats



Arable land required to organically produce 1,000 kg of target food
(acres)
2,5
2,0
1,5
1,0
0,5
0,0
Rice
Corn
Soybean
Leafy green vegetables
Cruciferous vegetables
Fruit
Coconut
Avocado
Sweet Potato
Seafood fish meat
Dairy Products
Poultry chicken meat
Eggs
Rice
Corn
Soybean
Leafy green vegetables
Cruciferous vegetables
Fruit
Coconut
Avocado
Sweet Potato
Animal feed soybean
Free range animal grazing
Animal feed - corn
Animal feed - barley
Animal feed - oats


Food for human consumption
16 000 kg rice
6 000 kg corn
2 000 kg soybeans
9 000 kg leafy green vegetables
7 000 kg cruciferous vegetables
5 000 kg fruit
4 000 kg coconuts
3 200 kg avocados
12 000 kg sweet potato's
6 000 kg chicken meat
6 000 kg eggs
2 400 kg pork meat
17 264 kg diary products
5 000 kg fish meat
20 acres arable land growing vegetables
Bee hives in 2 locations
200 person hamlet annual footprint (108 acres)
550 chickens
445 hens
37 pigs
3 dairy cows
68 acres arable land for free range grazing
27.5% share of an aquaculture farm
25 000 kg seaweed kelp
54 497 kg chicken manure
94 535 kg pig manure
52 500 kg cow manure
67 473 kg green waste
18 500 kg ash
246.7 tonne green waste
Organic fertilizer production
41 210 kg corn
7.6 acres arable land
16 403 kg barley
5.1 acres arable land
7 802 kg oats
3.9 acres arable land
3 501 kg soybeans
2.3 acres arable land
Feed for animals in hamlet
4 003 kg corn
0.8 acres arable land
801 kg soybeans
0.5 acres arable land
Feed for fish
GTK

200 person hamlet layout, season 2



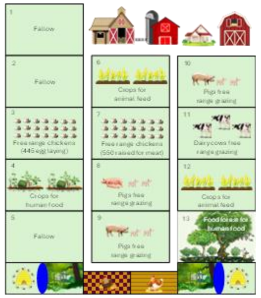
11 acre field	Seasons of Year (each 3 months)			
	1	2	3	4
1	Crop human feed	Fallow	Chicken grazing (meat)	Pigs grazing
2	Crop animal feed	Fallow	Chicken grazing (eggs)	Pigs grazing
3	Crop animal feed	Chicken grazing (eggs)	Cows grazing	Pigs grazing
4	Pigs grazing	Crop human feed	Pigs grazing	Chicken grazing (meat)
5	Pigs grazing	Fallow	Fallow	Crop animal feed
6	Pigs grazing	Crop animal feed	Fallow	Chicken grazing (eggs)
7	Fallow	Chicken grazing (meat)	Fallow	Cows grazing
8	Chicken grazing (meat)	Pigs grazing	Pigs grazing	Crop animal feed
9	Chicken grazing (eggs)	Pigs grazing	Crop human feed	Fallow
10	Cows grazing	Pigs grazing	Crop animal feed	Fallow
11	Fallow	Cows grazing	Crop animal feed	Fallow
12	Fallow	Crop animal feed	Pigs grazing	Crop human feed
13	Food forest for human food			
143	(acres total)			

Demand for Nitrogen Nutrients

7
N
NITROGEN

- 16,000 kg of rice — 120 kg N
- 6,000 kg of corn — 117 kg N
- 2,000 kg of soybeans — 64 kg N
- 9,000 kg of leafy green vegetables — 135 kg N
- 7,000 kg of cruciferous vegetables — 95 kg N
- 5,000 kg of fruit — 17 kg N
- 4,000 kg of coconuts — 124 kg N
- 3,200 kg of avocados — 389 kg N
- 12,000 kg of sweet potato — 277 kg N

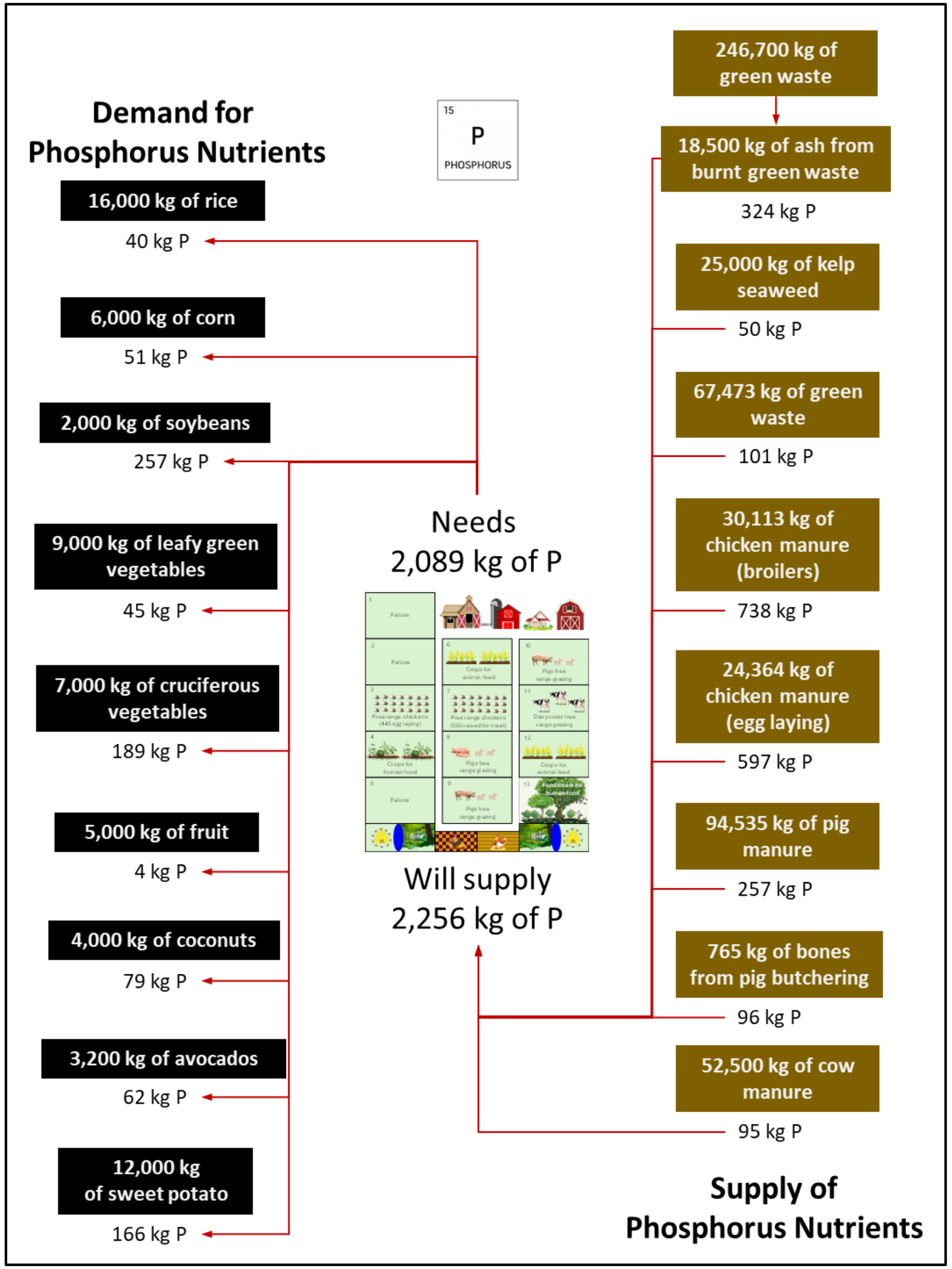
Needs
2,969 kg of N



Will supply
2,911 kg of N

Supply of Nitrogen Nutrients

- 25,000 kg of kelp seaweed — 325 kg N
- 67,473 kg of green waste — 337 kg N
- 30,113 kg of chicken manure (broilers) — 874 kg N
- 24,364 kg of chicken manure (egg laying) — 707 kg N
- 94,535 kg of pig manure — 385 kg N
- 765 kg of bones from pig butchering — 46 kg N
- 52,500 kg of cow manure — 237 kg N


Demand for Phosphorus Nutrients
15
P
PHOSPHORUS
16,000 kg of rice
40 kg P
6,000 kg of corn
51 kg P
2,000 kg of soybeans
257 kg P
9,000 kg of leafy green vegetables
45 kg P
7,000 kg of cruciferous vegetables
189 kg P
5,000 kg of fruit
4 kg P
4,000 kg of coconuts
79 kg P
3,200 kg of avocados
62 kg P
12,000 kg of sweet potato
166 kg P
Needs
2,089 kg of P
Will supply
2,256 kg of P
246,700 kg of green waste
18,500 kg of ash from burnt green waste
324 kg P
25,000 kg of kelp seaweed
50 kg P
67,473 kg of green waste
101 kg P
30,113 kg of chicken manure (broilers)
738 kg P
24,364 kg of chicken manure (egg laying)
597 kg P
94,535 kg of pig manure
257 kg P
765 kg of bones from pig butchering
96 kg P
52,500 kg of cow manure
95 kg P
Supply of Phosphorus Nutrients

Demand for Potassium Nutrients

K
Potassium

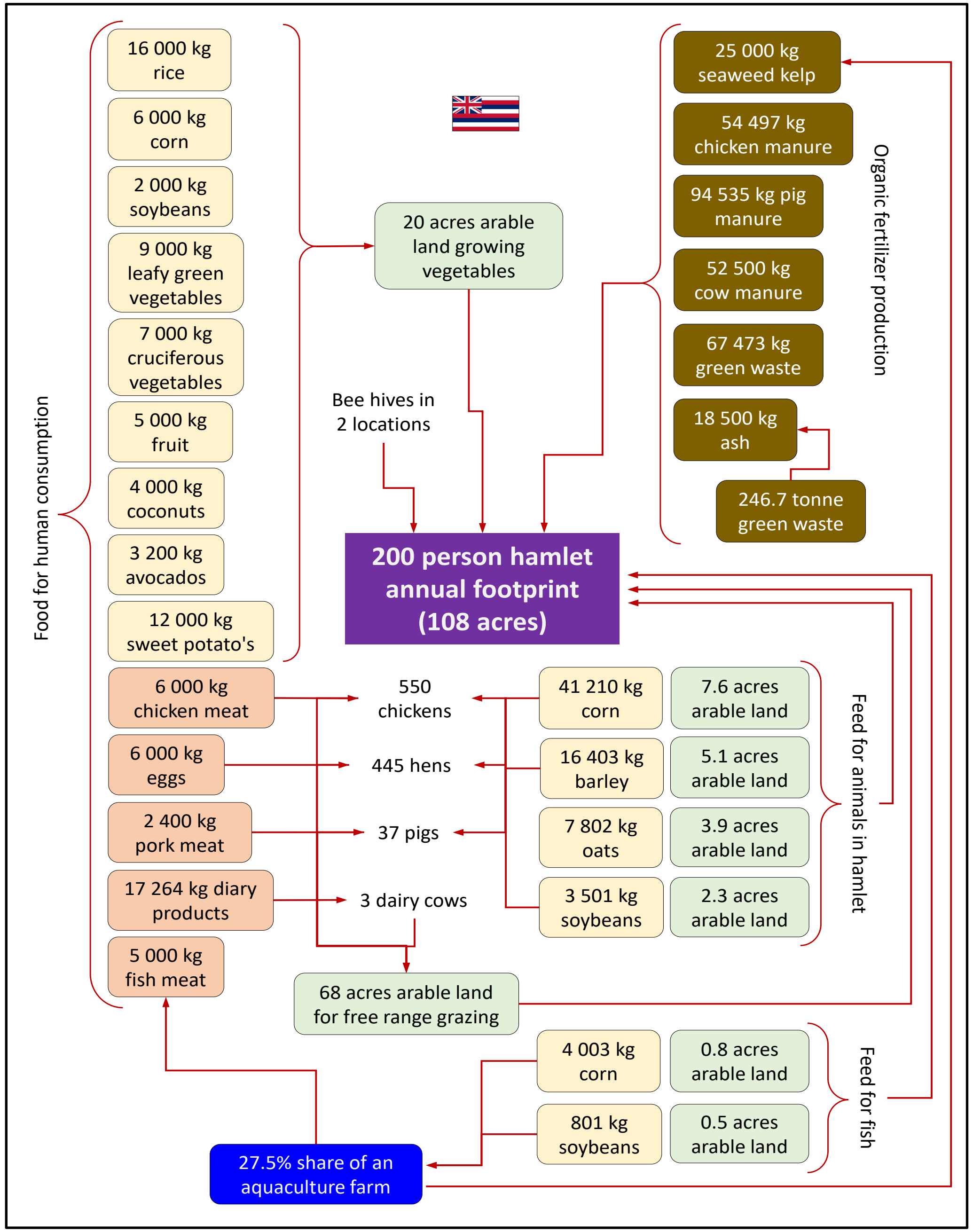
- 16,000 kg of rice — 40 kg K
- 6,000 kg of corn — 117 kg K
- 2,000 kg of soybeans — 128 kg K
- 9,000 kg of leafy green vegetables — 95 kg K
- 7,000 kg of cruciferous vegetables — 95 kg K
- 5,000 kg of fruit — 42 kg K
- 4,000 kg of coconuts — 298 kg K
- 3,200 kg of avocados — 446 kg K
- 12,000 kg of sweet potato — 463 kg K

Needs
3,134 kg of K

Will supply
3,157 kg of K

- 246,700 kg of green waste → 18,500 kg of ash from burnt green waste — 1,110 kg K
- 25,000 kg of kelp seaweed — 500 kg K
- 67,473 kg of green waste — 0.5 kg K
- 30,113 kg of chicken manure (broilers) — 656 kg K
- 24,364 kg of chicken manure (egg laying) — 531 kg K
- 94,535 kg of pig manure — 171 kg K
- 52,500 kg of cow manure — 189 kg K

Supply of Potassium Nutrients



Food for human consumption
16 000 kg rice
6 000 kg corn
2 000 kg soybeans
9 000 kg leafy green vegetables
7 000 kg cruciferous vegetables
5 000 kg fruit
4 000 kg coconuts
3 200 kg avocados
12 000 kg sweet potato's
20 acres arable land growing vegetables
Bee hives in 2 locations
200 person hamlet annual footprint (108 acres)
25 000 kg seaweed kelp
54 497 kg chicken manure
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52 500 kg cow manure
67 473 kg green waste
18 500 kg ash
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5 000 kg fish meat
550 chickens
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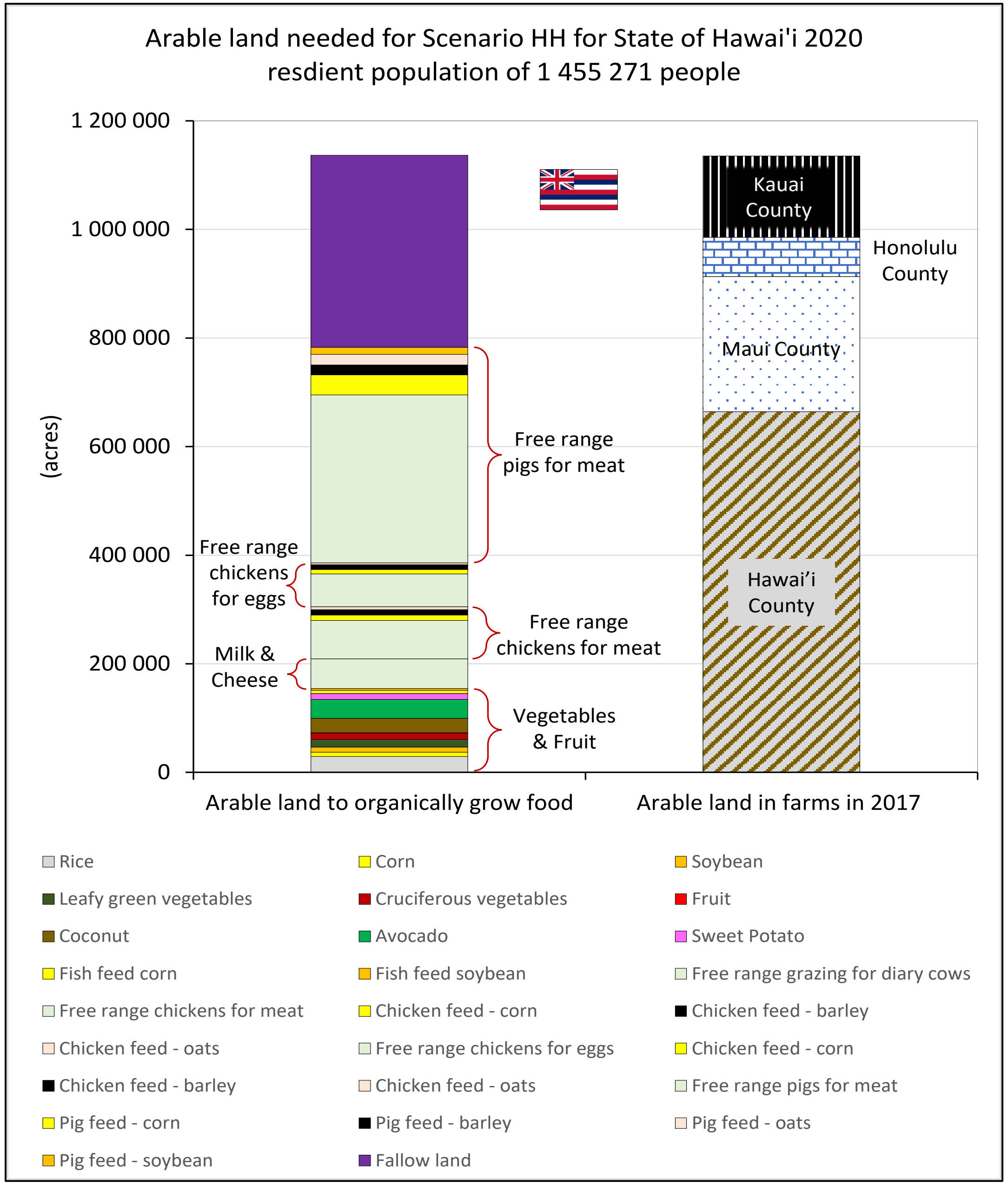
7.6 acres arable land
5.1 acres arable land
3.9 acres arable land
2.3 acres arable land
Feed for animals in hamlet
68 acres arable land for free range grazing
4 003 kg corn
801 kg soybeans
0.8 acres arable land
0.5 acres arable land
Feed for fish
27.5% share of an aquaculture farm

GTK


Arable land needed for Scenario HH for State of Hawai'i 2020
resdient population of 1 455 271 people
1 200 000
1 000 000
800 000
600 000
400 000
200 000
0
(acres)
Kauai County
Honolulu County
Maui County
Hawai'i County
Free range pigs for meat
Free range chickens for eggs
Free range chickens for meat
Milk & Cheese
Vegetables & Fruit
Arable land to organically grow food
Arable land in farms in 2017
Rice
Corn
Soybean
Leafy green vegetables
Cruciferous vegetables
Fruit
Coconut
Avocado
Sweet Potato
Fish feed corn
Fish feed soybean
Free range grazing for diary cows
Free range chickens for meat
Chicken feed - corn
Chicken feed - barley
Chicken feed - oats
Free range chickens for eggs
Chicken feed - corn
Chicken feed - barley
Chicken feed - oats
Free range pigs for meat
Pig feed - corn
Pig feed - barley
Pig feed - oats
Pig feed - soybean
Fallow land

What are we really trying to do?

We want electricity generation

We want transport

We want manufacture

Reliable and consistently stable power generation in all weathers, in all geographical regions

Preferably in concentrated form

Preferably with a low materials footprint

A long working life

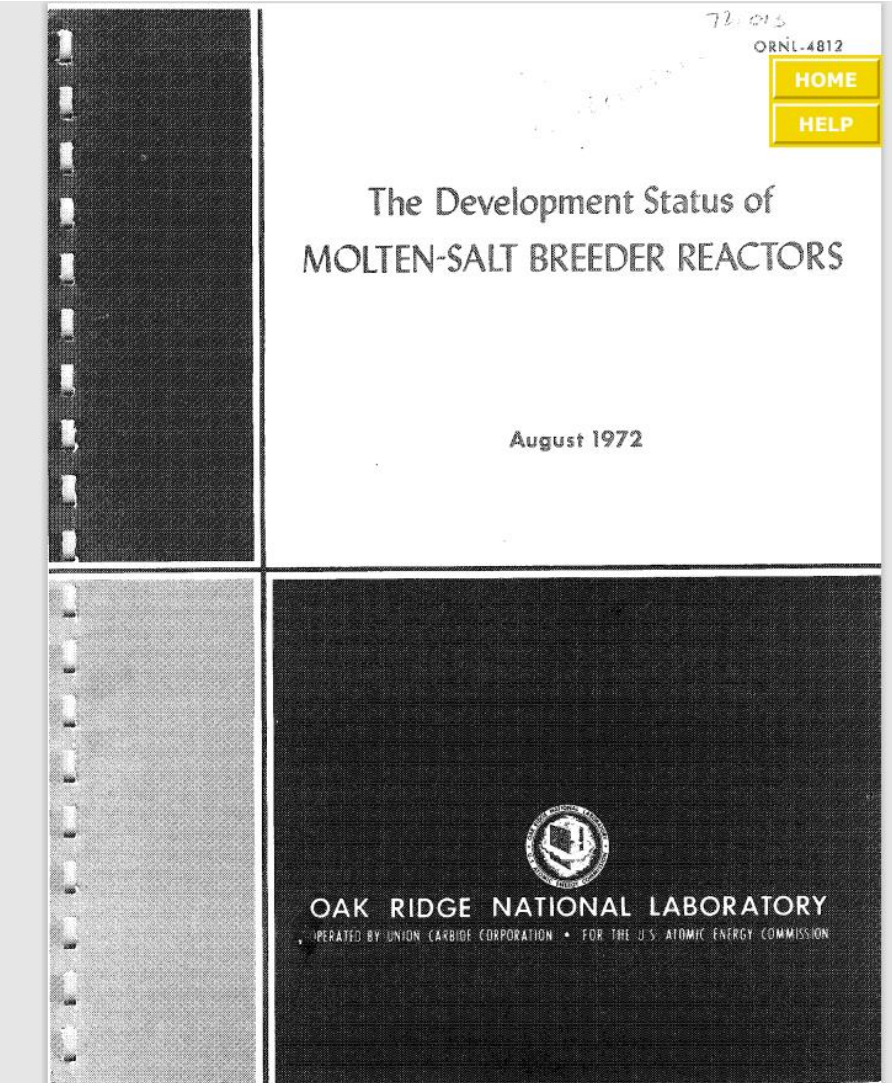
Designed to be recycled

Minimal waste plume with very low environmental impact

If the Green Transition won’t work, what might we do instead?

Scenario HI – The Purple Transition

- Resource Balanced Economy
  - The Circular Economy evolved & reinvented
- Liquid fuel fission: thorium fueled molten salt modular reactors
  - Generation of electricity & heat at (560 ^{o}C)
- Electric Vehicles: powered by alternative battery chemistries
  - Not Lithium-ion chemistry systems
  - Short range transport less than 100 km, applied in cities
- Combustion of iron powder as a thermal fuel
  - High temperature fuel (1960 ^{o}C)
  - To replace coal as a thermal fuel in manufacture
- Pyrolysis of human sewage to produce syngas
  - Production of hydrogen assisting Sulfur Iodide Cycle
  - Recycle oxidized iron powder fuel
- Ammonia fueled ICE technology
  - Long range transport
  - Maritime shipping, intercity freight trains, possibly some aviation applications



72-013

ORNL-4812

HOME

HELP

The Development Status of

MOLTEN-SALT BREEDER REACTORS

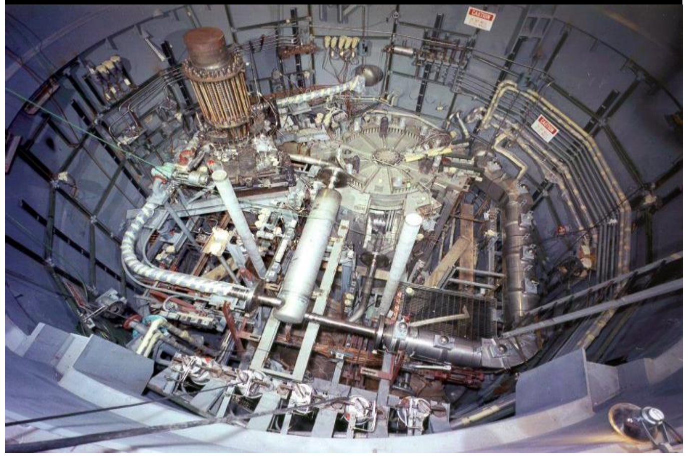
August 1972

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

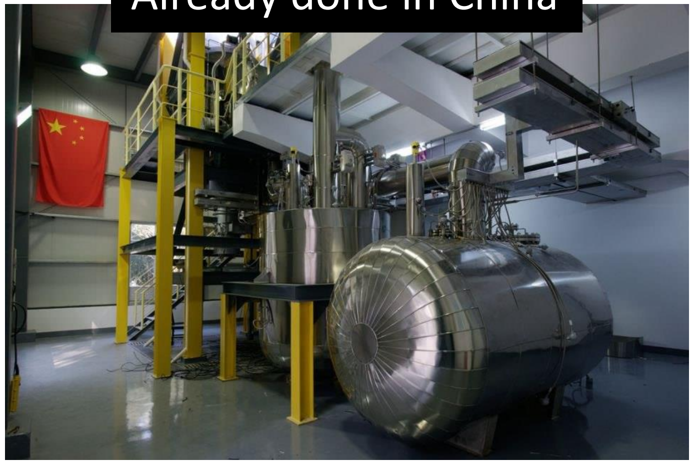
ORNL (1972): The Development Status of Molten Salt Breeder Reactors, Report ORNL - 4812, Oak Ridge Nuclear Laboratory, United States Atomic Energy Commission (AEC)

6000 hours power generation

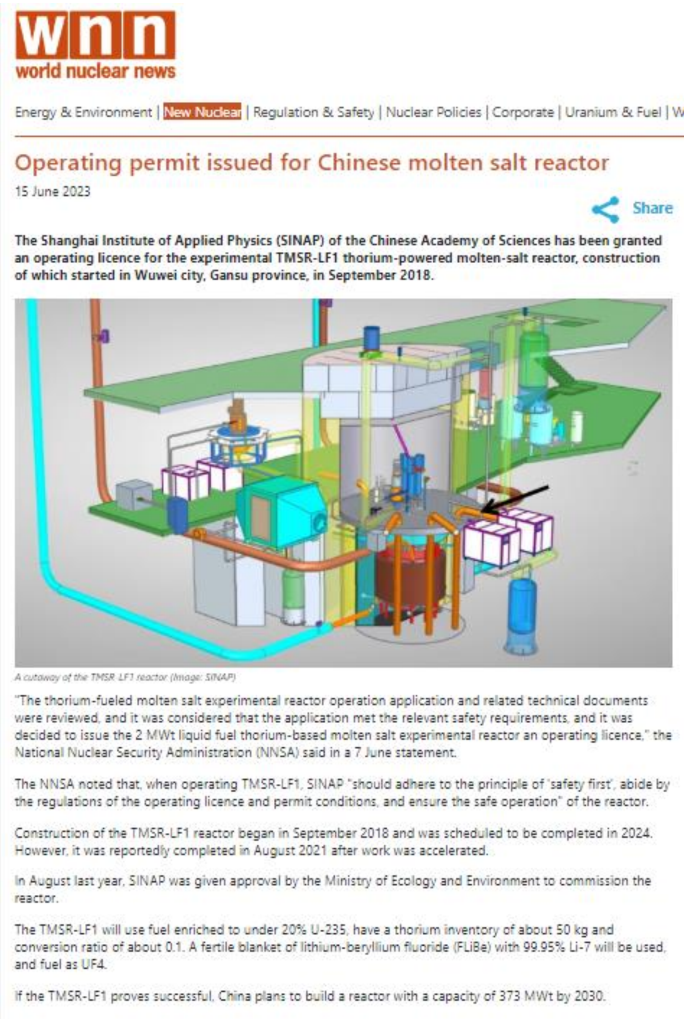


The MSR used in the Oak Ridge Molten salt rea
(7.4 MW) commercial pilot 1969

Already done in China



The LFTR (2 MW) used in Circa Whuhai, China
in 2022 – now commercially selling power



wnn
world nuclear news

Energy & Environment | New Nuclear | Regulation & Safety | Nuclear Policies | Corporate | Uranium & Fuel | W

Operating permit issued for Chinese molten salt reactor

15 June 2023

Share

The Shanghai Institute of Applied Physics (SINAP) of the Chinese Academy of Sciences has been granted an operating licence for the experimental TMSR-LF1 thorium-powered molten-salt reactor, construction of which started in Wuwei city, Gansu province, in September 2018.

A cutaway of the TMSR-LF1 reactor (Image: SINAP)

"The thorium-fueled molten salt experimental reactor operation application and related technical documents were reviewed, and it was considered that the application met the relevant safety requirements, and it was decided to issue the 2 MWt liquid fuel thorium-based molten salt experimental reactor an operating licence," the National Nuclear Security Administration (NNSA) said in a 7 June statement.

The NNSA noted that, when operating TMSR-LF1, SINAP "should adhere to the principle of 'safety first', abide by the regulations of the operating licence and permit conditions, and ensure the safe operation" of the reactor.

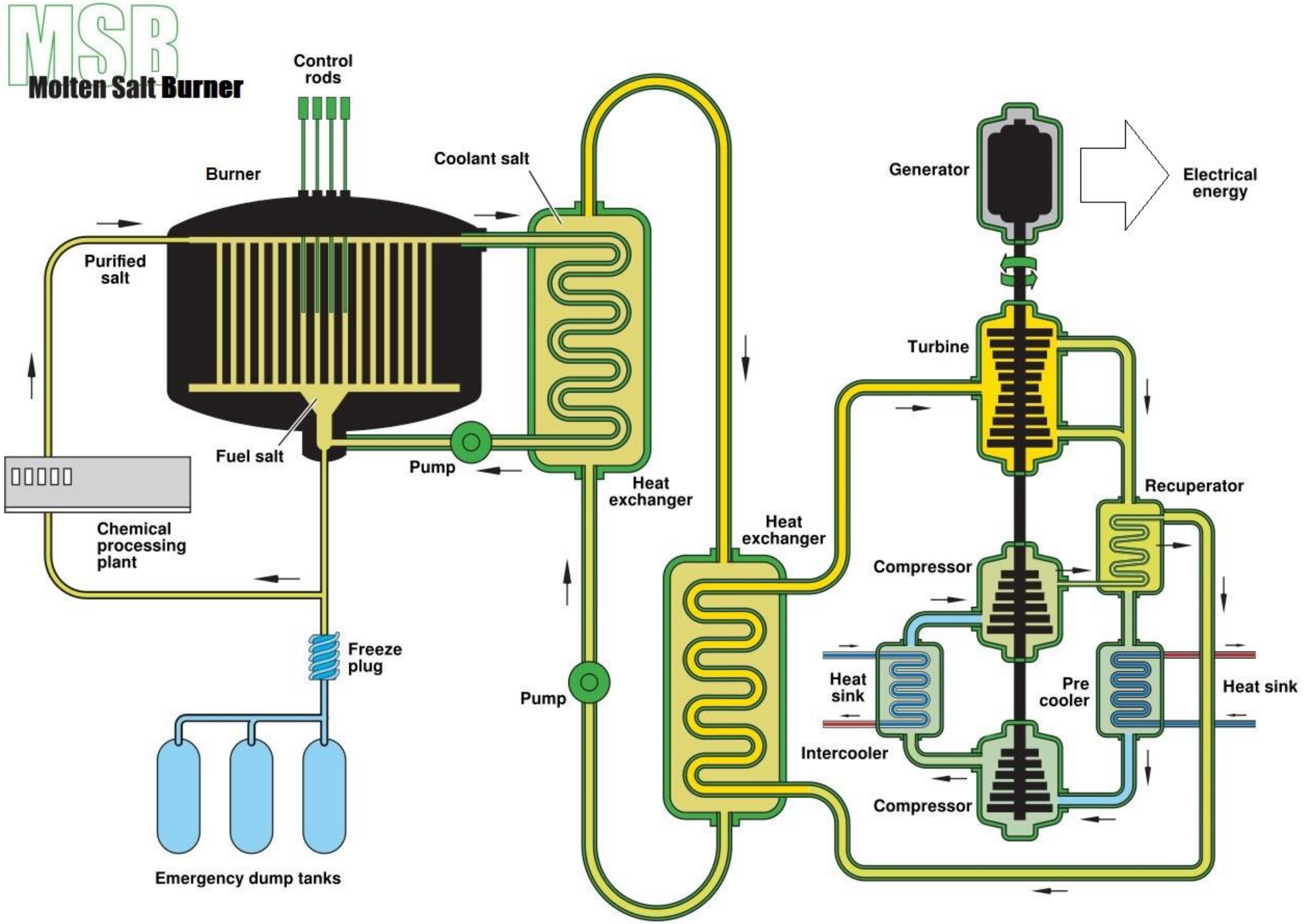
Construction of the TMSR-LF1 reactor began in September 2018 and was scheduled to be completed in 2024. However, it was reportedly completed in August 2021 after work was accelerated.

In August last year, SINAP was given approval by the Ministry of Ecology and Environment to commission the reactor.

The TMSR-LF1 will use fuel enriched to under 20% U-235, have a thorium inventory of about 50 kg and conversion ratio of about 0.1. A fertile blanket of lithium-beryllium fluoride (FLiBe) with 99.95% Li-7 will be used, and fuel as UF4.

If the TMSR-LF1 proves successful, China plans to build a reactor with a capacity of 373 MWt by 2030.

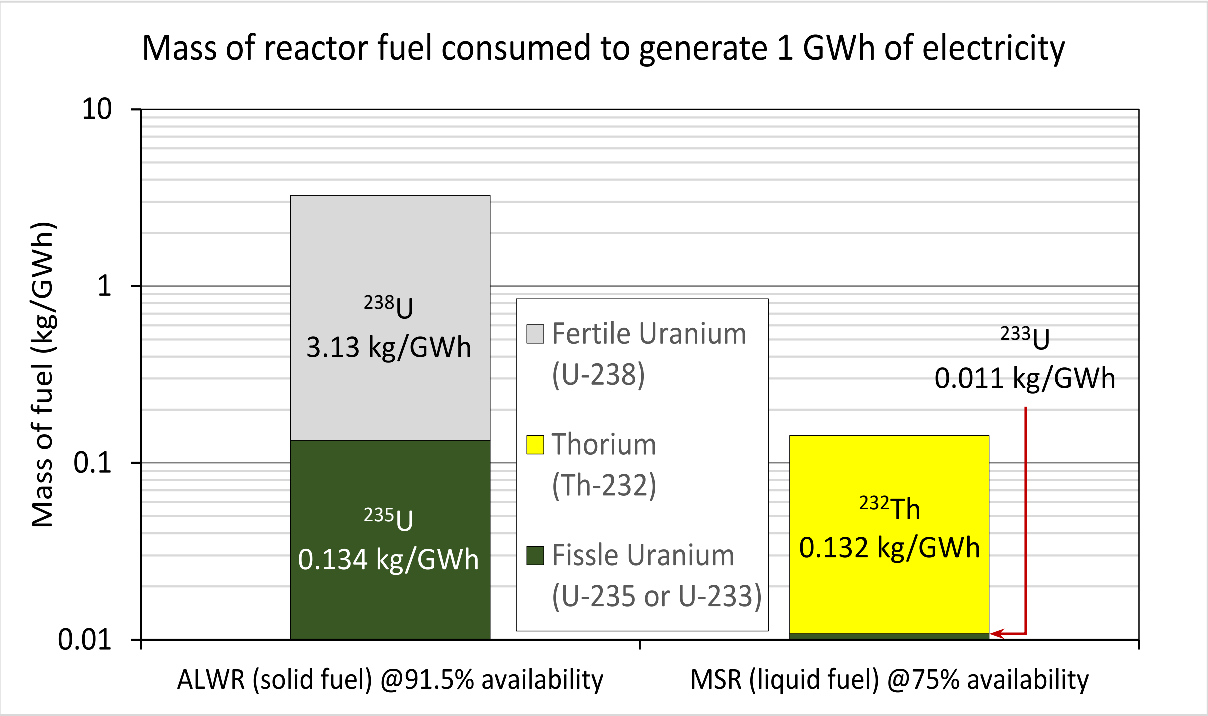
https://www.world-nuclear-news.org/Articles/Operating-permit-issued-for-Chinese-molten-salt-re



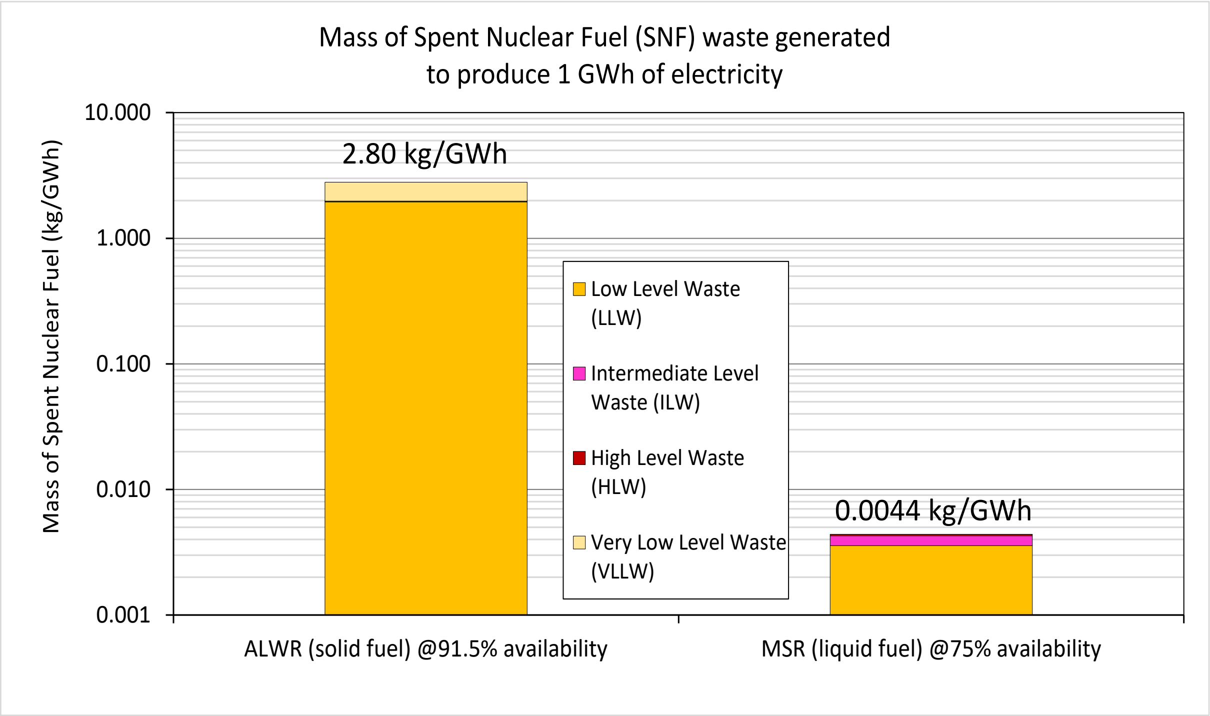
(Source: U.S. Department of Energy Nuclear Energy Research Advisory Committee)

Mass balance Th MSR to U ALWR to generate 1 GWh of electricity

Reactor fuel consumed



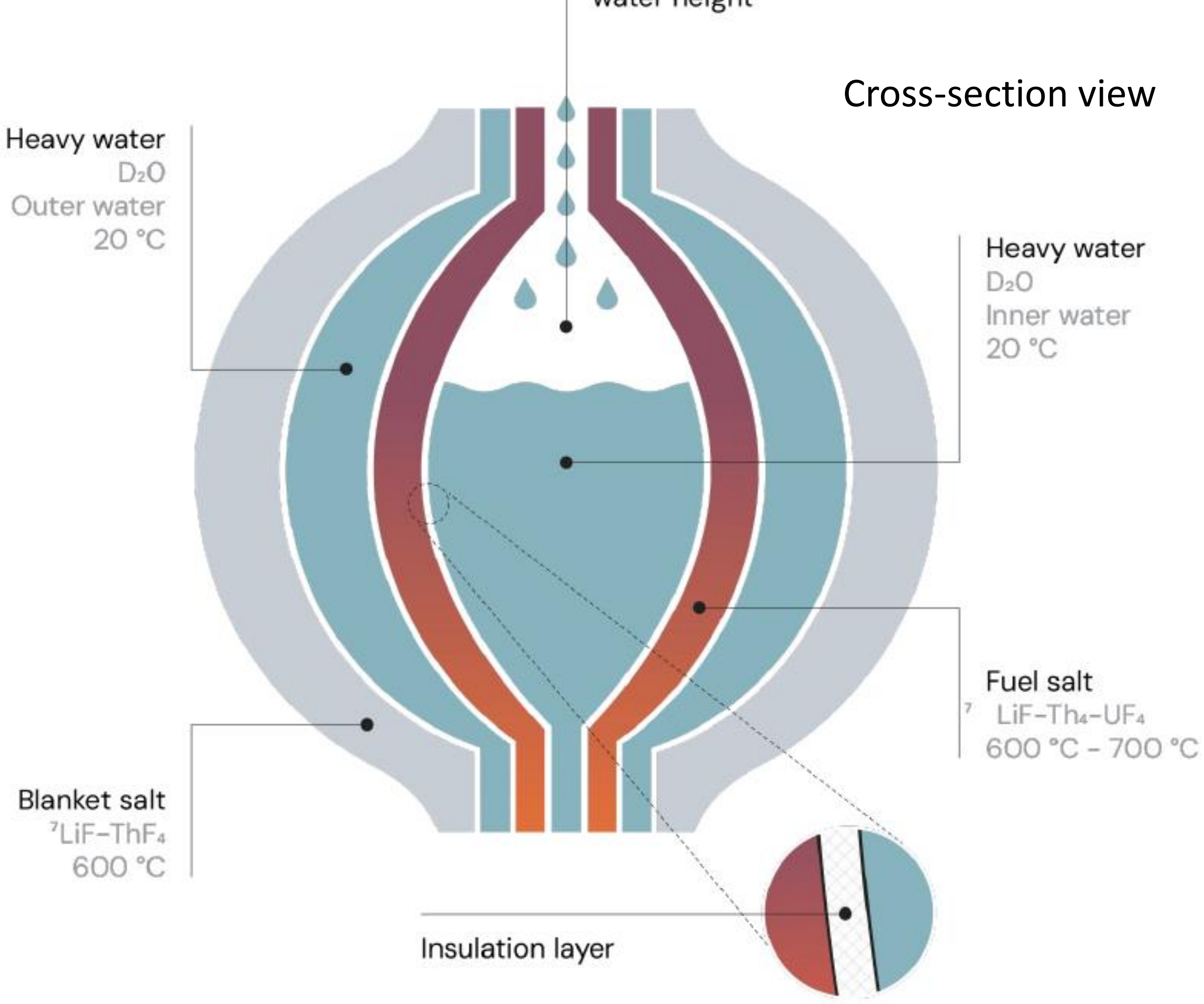
SNF waste produced



U	Th	U	Th
3.27 kg/GWh	**0.143 kg/GWh**	**2.80 kg/GWh**	**0.0044 kg/GWh**

Copenhagen Atomics- The Onion Core®

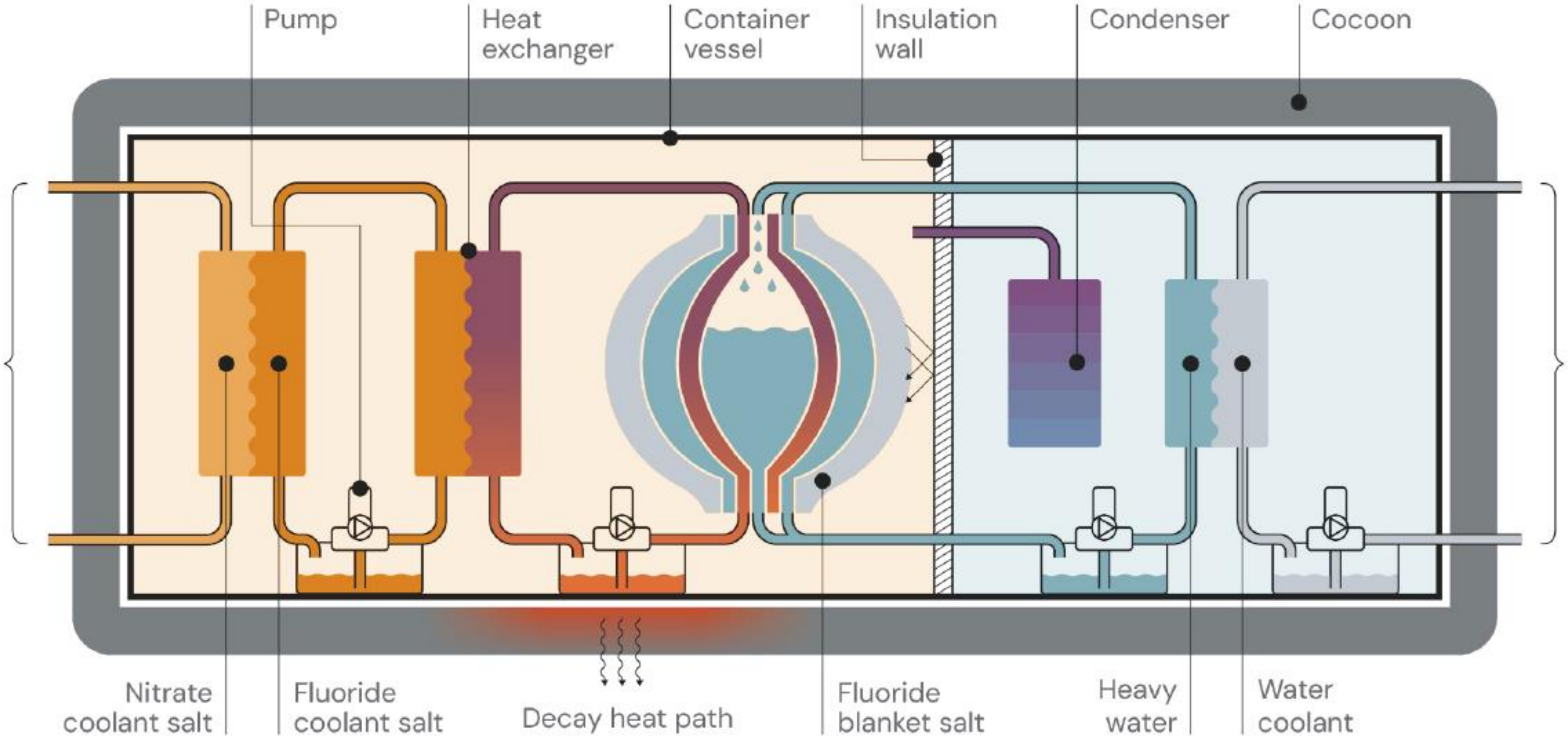
- Unpressurized room temperature heavy water moderator
- Double barrier and insulation between salt and heavy water
- segments made from metal or composite material
- Below 2% neutron leakage
- Reactivity control using heavy water level adjustment



copenhagen atomics

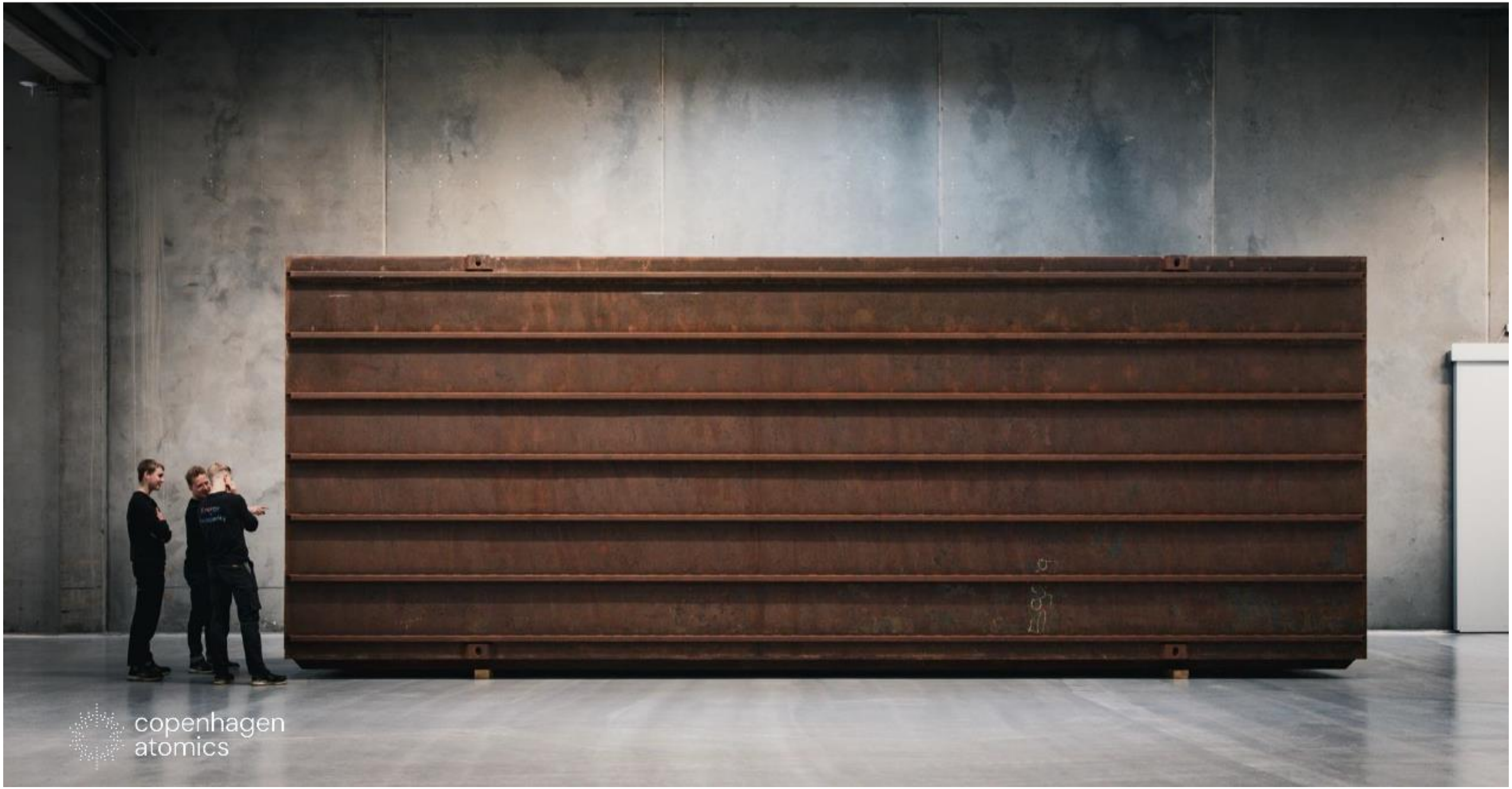
The Onion Core®

Loops and containment



copenhagen atomics

Non-fission prototype

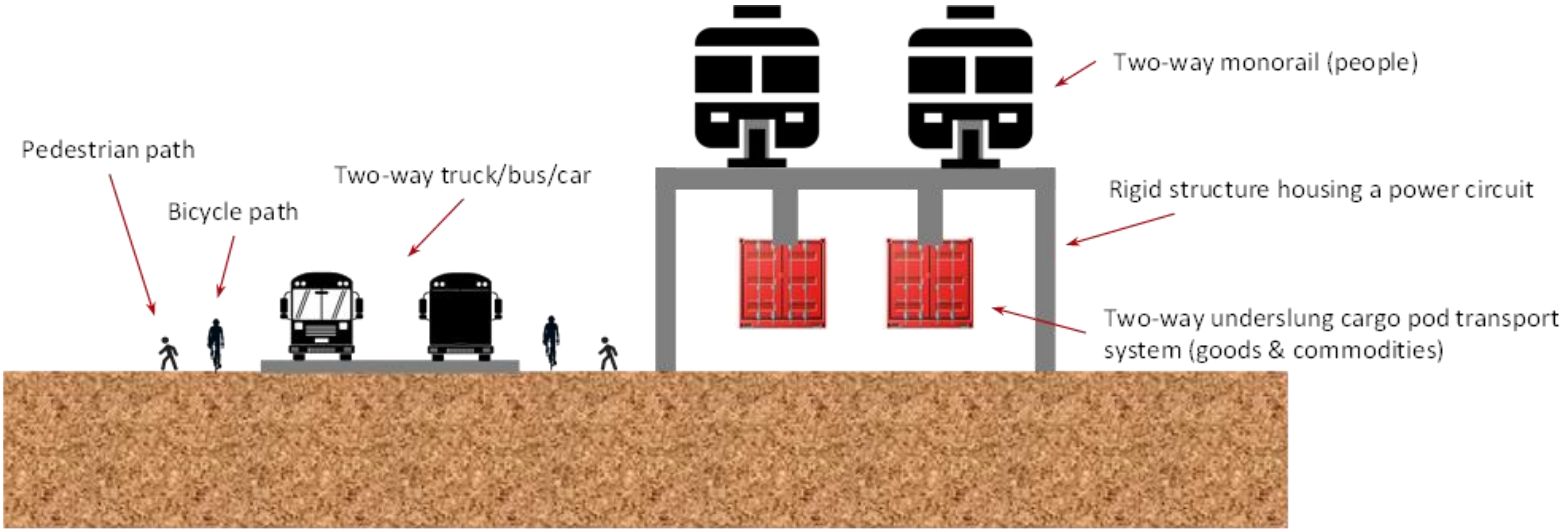


Copenhagen Atomics

- Each commercial rector is planned to be able to produce 100 MW of thermal heat, or 40 MW of electricity
  - *This is a modular system, where many units can be fitted together to construct a range of power capacities*
- Each reactor is the size of a 40 foot shipping container
- Electricity will be sold at a projected 2 cents/kWh
- 1g of thorium or uranium produces 24 MWh of thermal energy.
  - *A plant producing 1 GW electricity needs 800kg of Th_{232} metal in salt form each year.*
- First test of complete system (1 MW) to generate electricity in late 2026
- Reactors will be available for the sale of electricity in 2028 (at this stage)
  - *Copenhagen Atomic will not sell the reactors. They will finance, build, own and operate them for the customer.*

Test rig with a full sized reactor to pilot test the water circuit

https://www.copenhagenatomics.com/


Two-way monorail (people)
Pedestrian path
Two-way truck/bus/car
Rigid structure housing a power circuit
Bicycle path
Two-way underslung cargo pod transport system (goods & commodities)

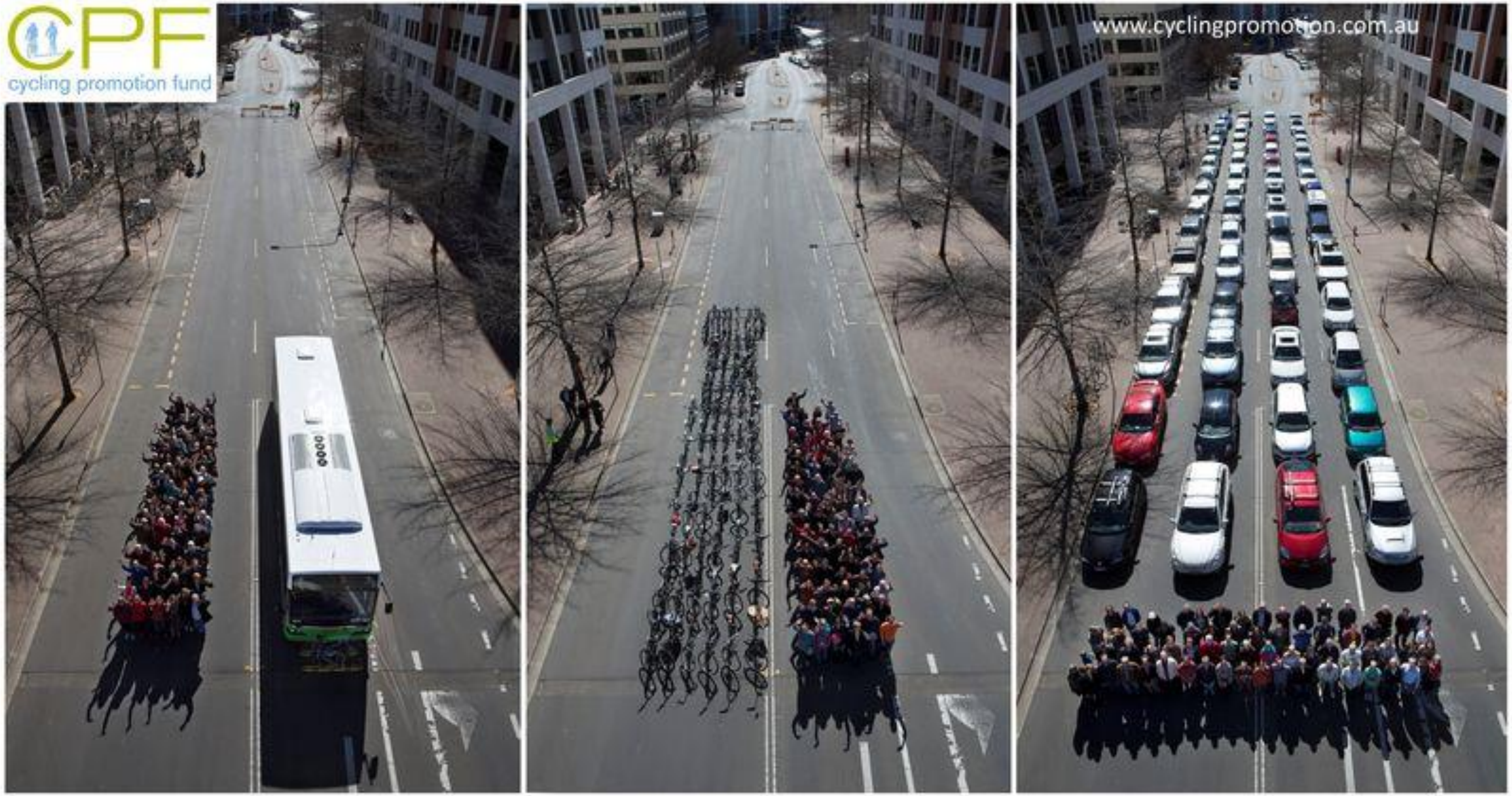


Figure 169. Comparison of 90 passengers on a single public bus (LHS), the same number of people on bicycles (centre), the same number of people in 50 passenger cars (RHS) (Image & copyright Australia's Cycling Promotion Fund)

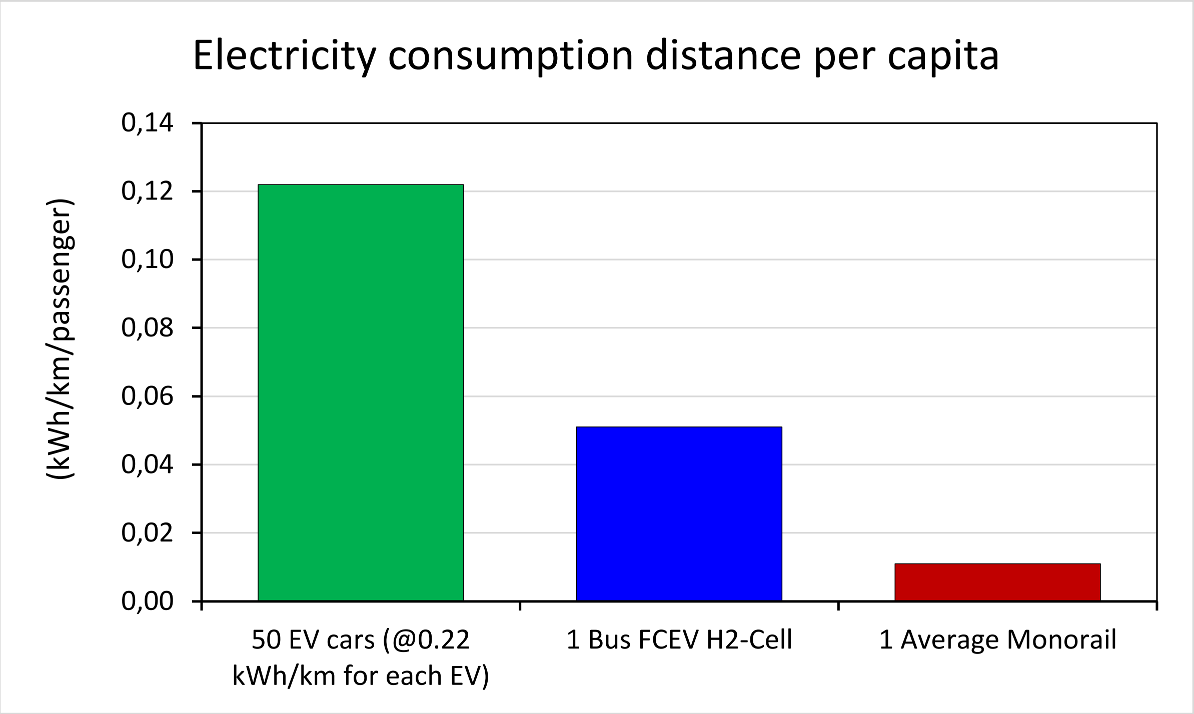


Figure 172. Electricity consumption for the transit of passengers

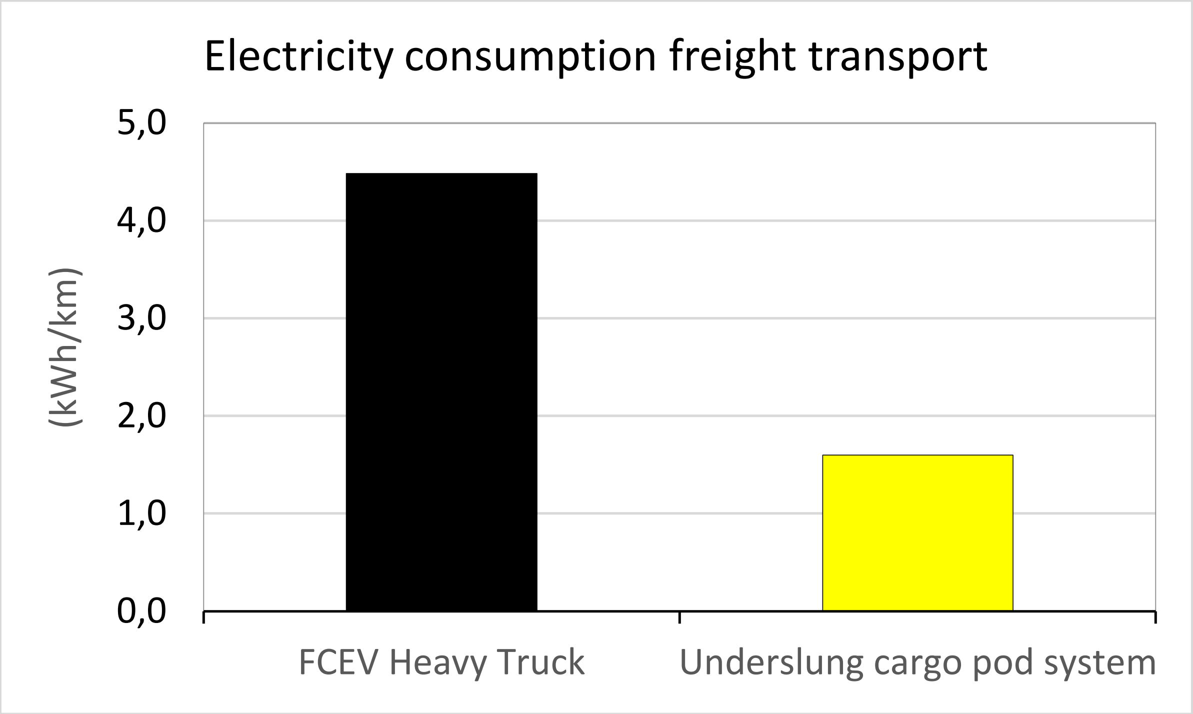
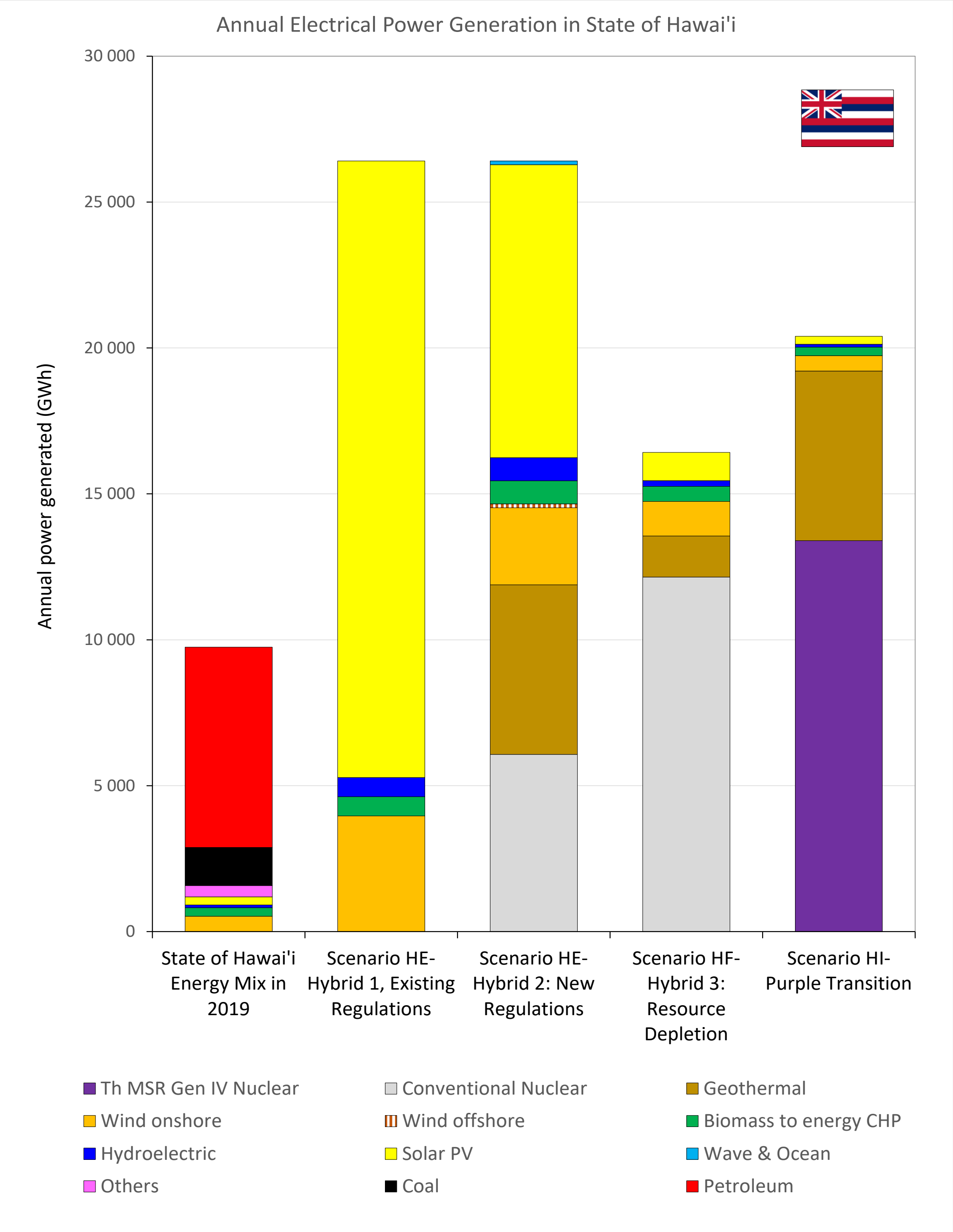
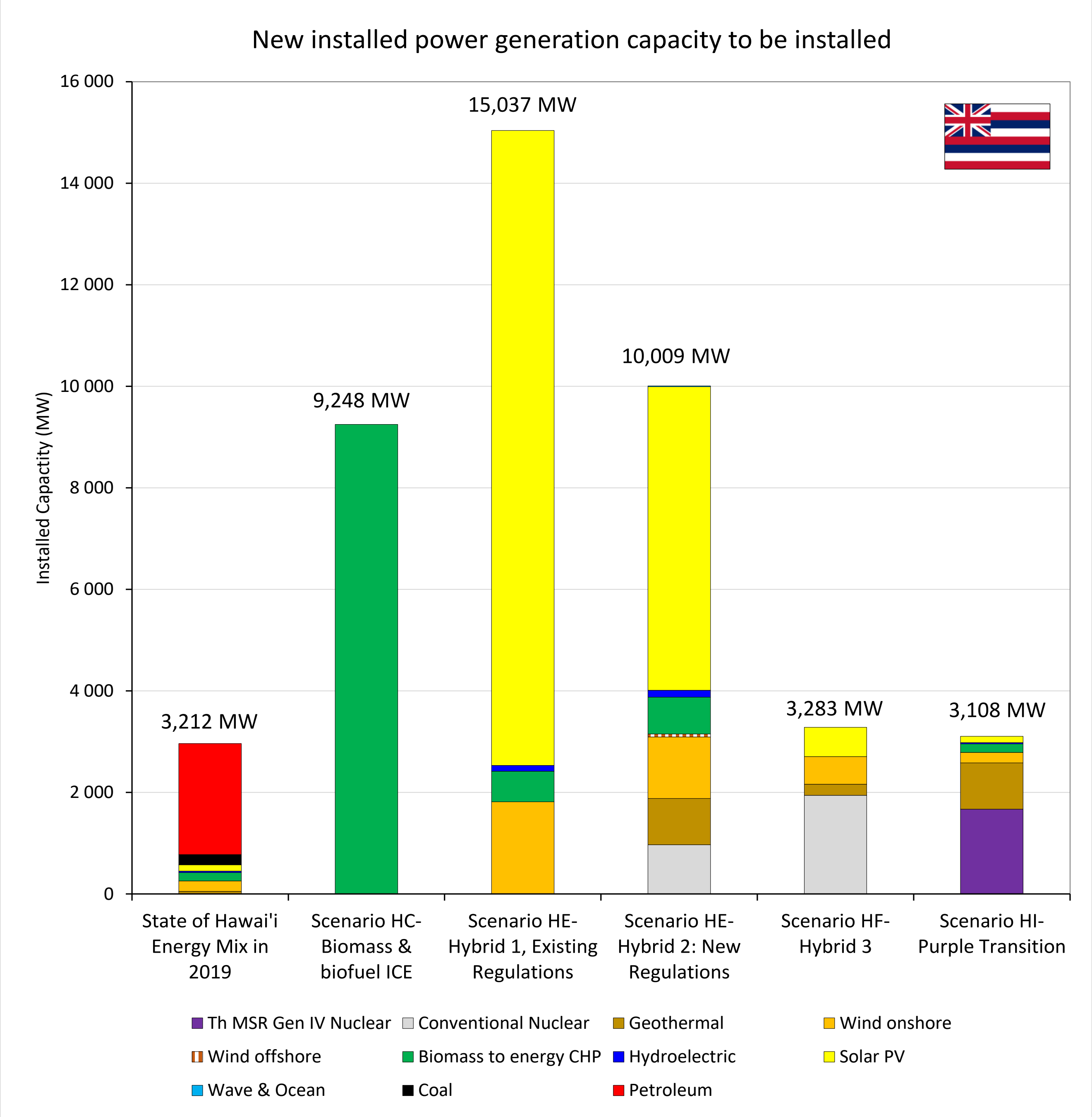


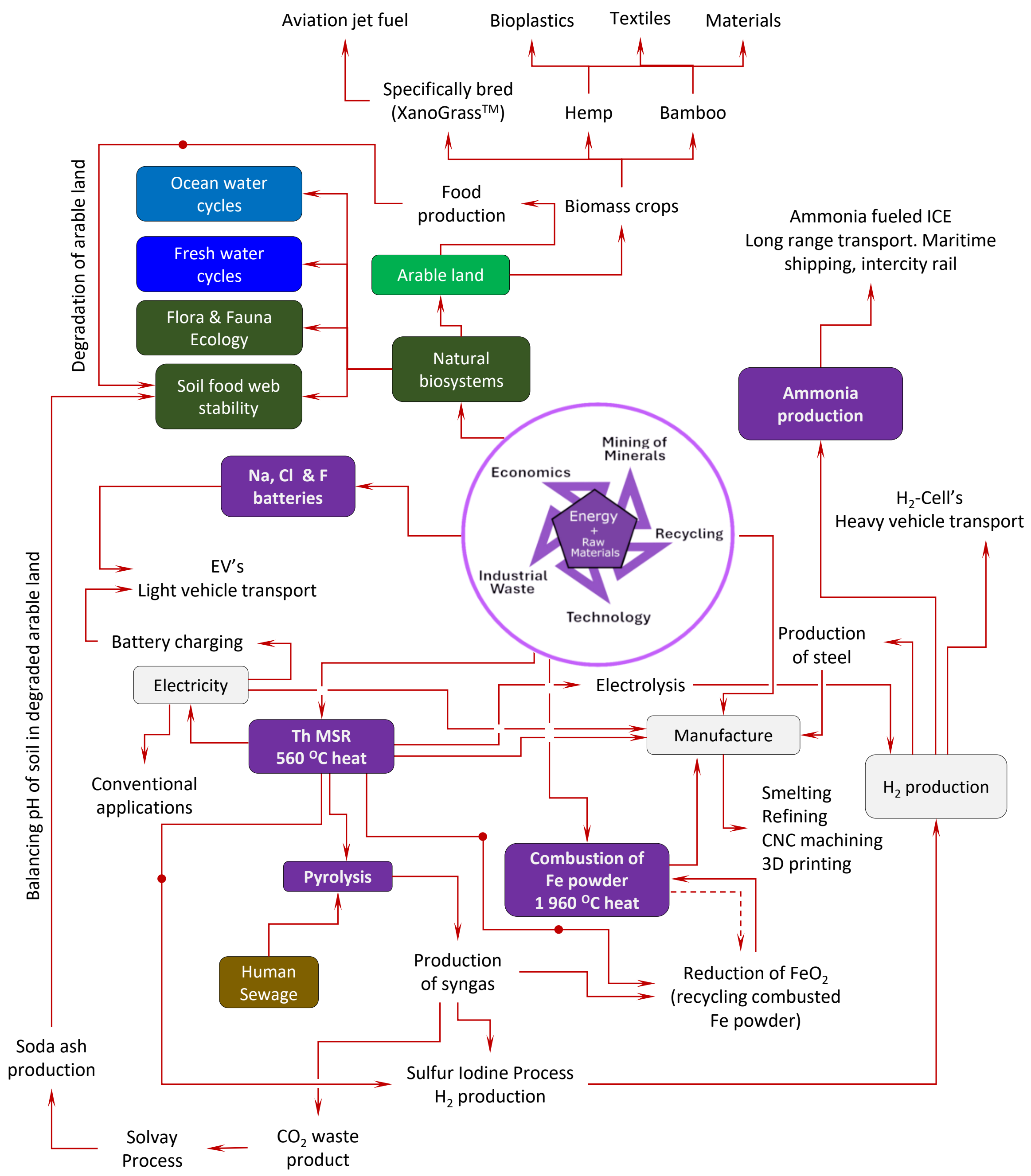
Figure 175. Electricity consumption for the transport of freight cargo



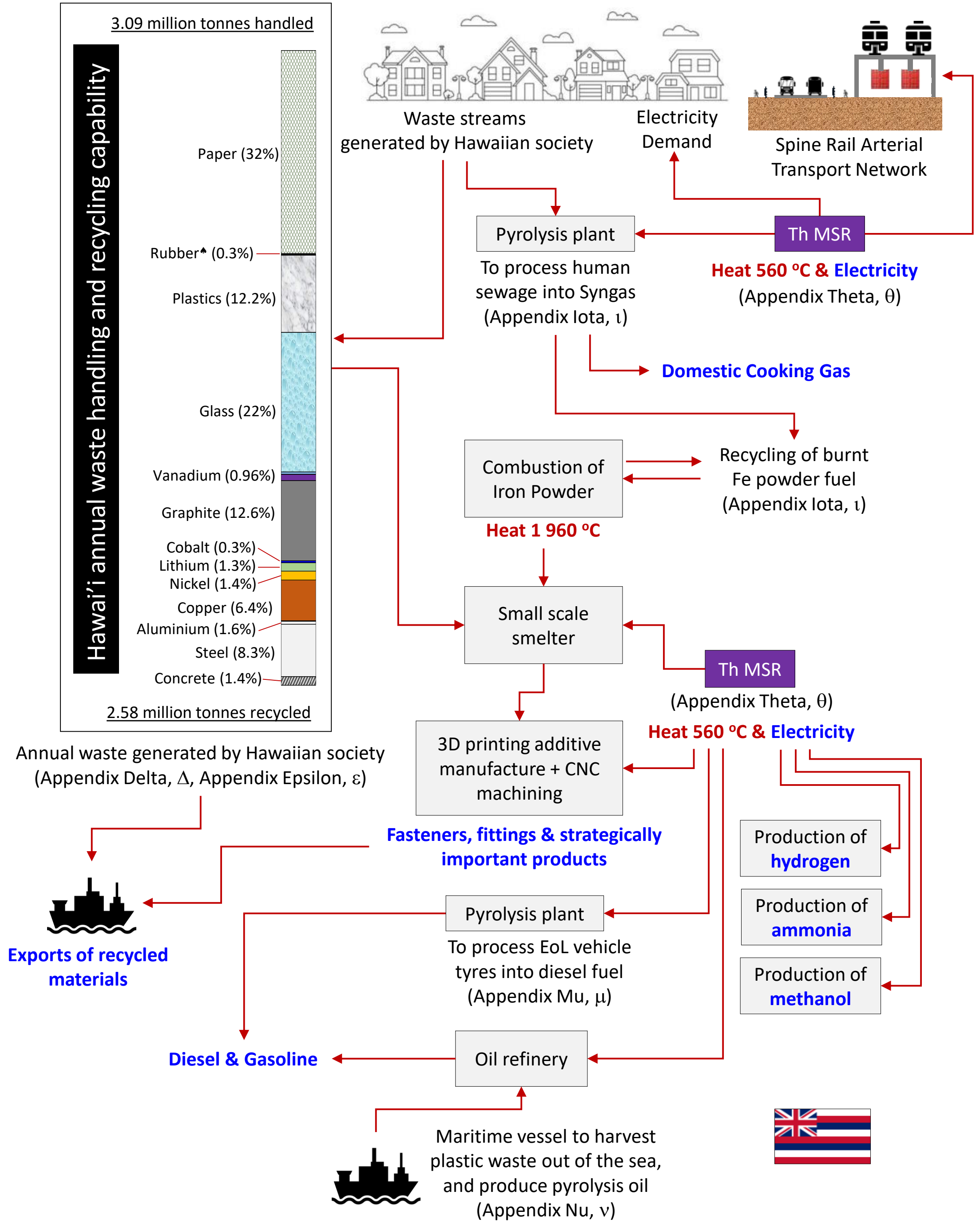
Annual Electrical Power Generation in State of Hawai'i
Annual power generated (GWh)
30 000
25 000
20 000
15 000
10 000
5 000
0
State of Hawai'i Energy Mix in 2019
Scenario HE-Hybrid 1, Existing Regulations
Scenario HE-Hybrid 2: New Regulations
Scenario HF-Hybrid 3: Resource Depletion
Scenario HI-Purple Transition
Th MSR Gen IV Nuclear
Conventional Nuclear
Geothermal
Wind onshore
Wind offshore
Biomass to energy CHP
Hydroelectric
Solar PV
Wave & Ocean
Others
Coal
Petroleum



New installed power generation capacity to be installed
Installed Capacity (MW)
16 000
14 000
12 000
10 000
8 000
6 000
4 000
2 000
0
3,212 MW
9,248 MW
15,037 MW
10,009 MW
3,283 MW
3,108 MW
State of Hawai'i Energy Mix in 2019
Scenario HC-Biomass & biofuel ICE
Scenario HE-Hybrid 1, Existing Regulations
Scenario HE-Hybrid 2: New Regulations
Scenario HF-Hybrid 3
Scenario HI-Purple Transition
Th MSR Gen IV Nuclear
Conventional Nuclear
Geothermal
Wind onshore
Wind offshore
Biomass to energy CHP
Hydroelectric
Solar PV
Wave & Ocean
Coal
Petroleum



Aviation jet fuel
Bioplastics
Textiles
Materials
Specifically bred (XanoGrass™)
Hemp
Bamboo
Food production
Biomass crops
Ocean water cycles
Fresh water cycles
Flora & Fauna Ecology
Soil food web stability
Arable land
Natural biosystems
Degradation of arable land
Ammonia fueled ICE Long range transport. Maritime shipping, intercity rail
Ammonia production
Na, Cl & F batteries
Mining of Minerals
Economics
Energy + Raw Materials
Recycling
Industrial Waste
Technology
H_2-Cell's Heavy vehicle transport
EV's Light vehicle transport
Battery charging
Electricity
Production of steel
Electrolysis
Th MSR 560 °C heat
Manufacture
H_2 production
Conventional applications
Smelting
Refining
CNC machining
3D printing
Balancing pH of soil in degraded arable land
Pyrolysis
Combustion of Fe powder 1 960 °C heat
Human Sewage
Production of syngas
Reduction of FeO_2 (recycling combusted Fe powder)
Soda ash production
Sulfur Iodine Process H_2 production
Solvay Process
CO_2 waste product



3.09 million tonnes handled
Hawai'i annual waste handling and recycling capability
Paper (32%)
Rubber♠ (0.3%)
Plastics (12.2%)
Glass (22%)
Vanadium (0.96%)
Graphite (12.6%)
Cobalt (0.3%)
Lithium (1.3%)
Nickel (1.4%)
Copper (6.4%)
Aluminium (1.6%)
Steel (8.3%)
Concrete (1.4%)
2.58 million tonnes recycled
Annual waste generated by Hawaiian society (Appendix Delta, Δ, Appendix Epsilon, ε)
Waste streams generated by Hawaiian society
Electricity Demand
Spine Rail Arterial Transport Network
Pyrolysis plant
To process human sewage into Syngas (Appendix Iota, ι)
Th MSR
Heat 560 °C & Electricity
(Appendix Theta, θ)
Domestic Cooking Gas
Combustion of Iron Powder
Heat 1 960 °C
Recycling of burnt Fe powder fuel (Appendix Iota, ι)
Small scale smelter
Th MSR
(Appendix Theta, θ)
Heat 560 °C & Electricity
3D printing additive manufacture + CNC machining
Fasteners, fittings & strategically important products
Exports of recycled materials
Production of hydrogen
Production of ammonia
Production of methanol
Pyrolysis plant
To process EoL vehicle tyres into diesel fuel (Appendix Mu, μ)
Diesel & Gasoline
Oil refinery
Maritime vessel to harvest plastic waste out of the sea, and produce pyrolysis oil (Appendix Nu, ν)

Conclusions

- This task is much bigger than first thought
- A transport fleet split of EV's and H_2-Cells is appropriate
  - *Light short range should be EV*
  - *Heavy long range should be H_2-Cell*
- Wind and solar are going to struggle to be viable due to the required power storage requirements
- Biofuels should be reserved for aviation fuel only due to land requirements
- Conventional biomass feedstocks to produce biofuels like corn and soybean require too much arable land to be viable.
  - *Consider specially bred species to do this instead*
- All conventional approaches had practical bottlenecks that made them impractical for scaleup
  - *Recommend you look at Th MSR units very carefully*

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Circular Economy Solutions
simon.michaux@gtk.fi
gtk.fi

Kiitos
& Thank you