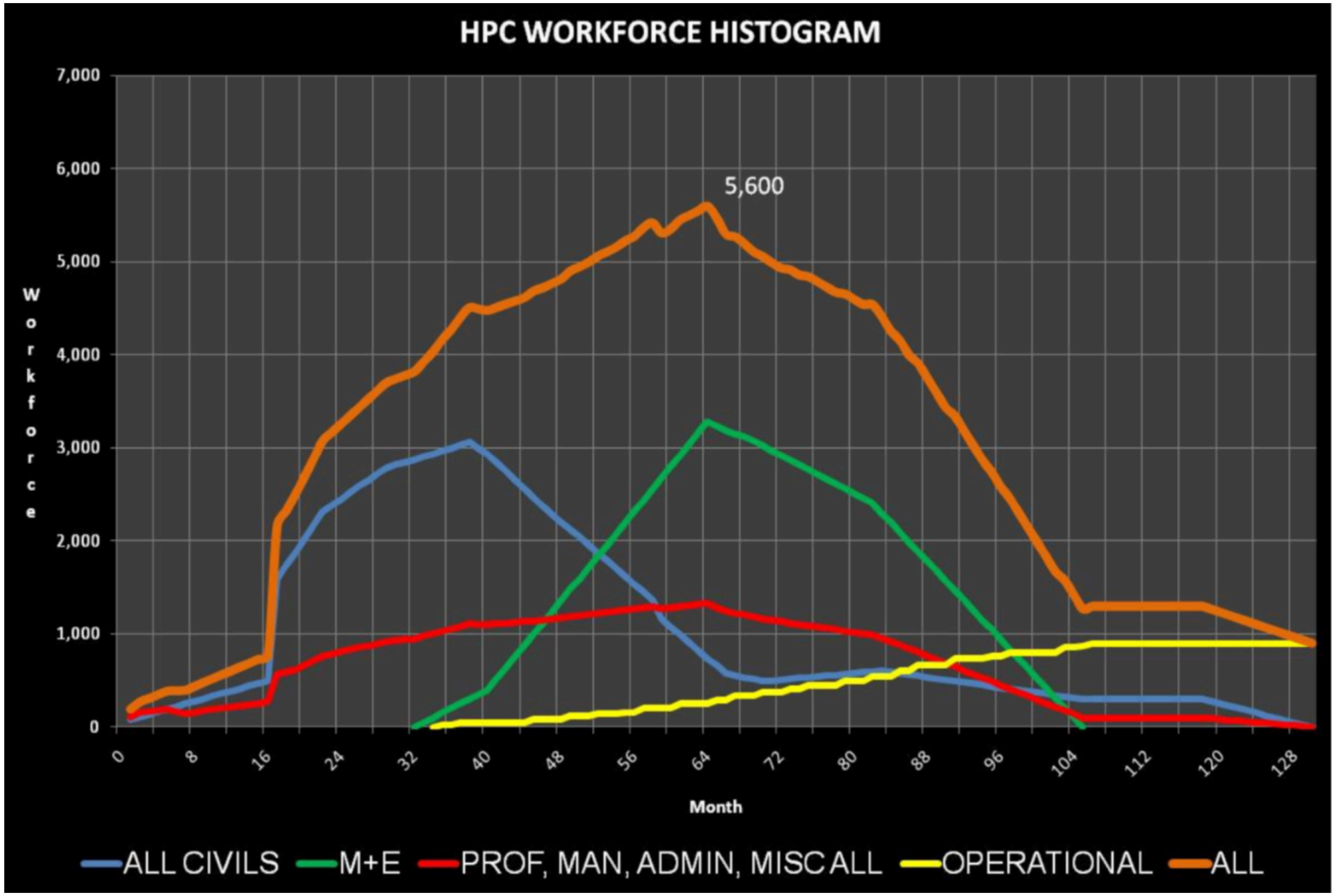
SMR cost estimate

- A cost estimate includes:
- Cost of construction
  - Mainly paid by utility to vendor - except for owner's cost.
  - Combined with the WACC, this gives you a value for CAPEX, the annual expenditure for capital costs.
- Operational expenditures: OPEX, including staff, maintentance, fuel, waste management and decommissioning fees.
- Levelised cost of electricity: LCOE
  - Sum of annual CAPEX and OPEX divided by power produced. Paid by consumer to utility - excludes transmission costs

Construction labour requirements



- Hinkley Point C on-site labour work force peaks at 5 600!

Cost for financing during construction

Duration of build	Fraction of total expenditures spent in year X							WACC: 6 %
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Financing cost
1 Y	100 %							3,0 %
2 Y	50 %	50 %						6,0 %
3 Y	30 %	40 %	30 %					9,2 %
4 Y	30 %	40 %	15 %	15 %				14,9 %
5 Y	30 %	40 %	15 %	7,5 %	7,5 %			21,8 %
6 Y	30 %	40 %	15 %	7,5 %	3,8 %	3,8 %		28,3 %
7 Y	30 %	40 %	15 %	7,5 %	2,5 %	2,5 %	2,5 %	35,8 %

Cost of construction

- The Generation IV International Forum (GIF) has defined ”cost accounts” to determine the total capital cost of novel reactor concepts

#	Capital cost item	LWR	Comment
10	Pre-construction		Land, site permits & plant licensing
20	Direct construction	1/3	See next slide
30	Indirect services	1/3	Equipment for on-site construction Supervision of construction Site related engineering
40	Owner’s costs		Staff salaries & training
50	Supplementary costs		Transportation, spare parts, taxes, insurance, decommissioning
60	Financing during construction	1/5	

Direct construction costs

#	Power	Comments
21	Buildings	1500 - 2000 €/m² (Conventional building, Sweden) 5000 €/m³ (Class 1 nuclear)
22	Reactor equipment	See next slide
23	Turbine equipment	15 MW plant: 670 USD/kWe (DoE)
24	Electrical equipment	Switchgear, raceways, cables
25	Heat rejection system	Water pumps, cooling towers
26	Miscellaneous	Air, water, fuel oil, steam services
27	Special materials	Coolant/moderator
28	Simulator	One per unique reactor design

Reactor equipment

Item	Comments
Materials	Steels, absorbers, reflectors
Core	Fuel, control, shut-down, reflector, shield SA
Pumps	
Heat exchanger	LFR: Steam generator
Vessels	Core barrel, primary vessel, guard vessel
Instrumentation	Flux, temperature, pressure, flow, level
Auxiliary	Cover gas and coolant conditioning, heating, filling/draining
Assembly	Levelised factory construction, maintenance & staff costs

Cost of vessel materials

- HTR: Stainless 316L steel, Thickness: 150 mm
- PWR:
  - Carbon steel, Thickness 150 - 220 mm
  - SS316L liner, Thickness 7 mm
- LFR
  - 316L steel, Thickness: 40 mm
  - Alumina forming austenitic (AFA) weld overlay, Thickness 3 mm

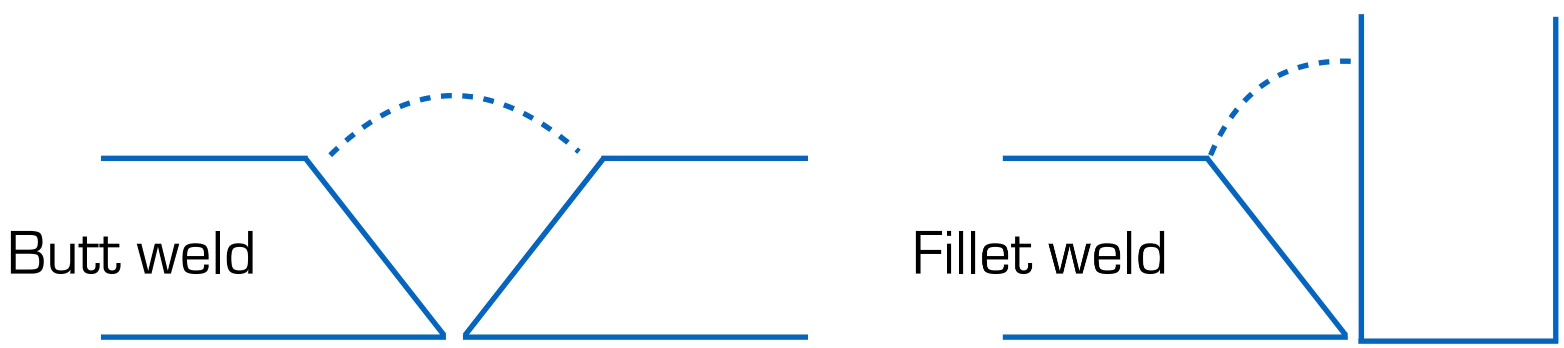
Steel	Specific cost
SS316L	2.3 USD/kg
Carbon steel	0.8 USD/kg
AFA	100 USD/kg

Cost of vessel manufacture

- In high level estimates, so called ”Lang Factors” may be applied to estimate the cost of manufacture.
- Lang factor multiples the materials cost.
- Based on set of actual industrial data
- Lang factor for manufacture of large vessels: ≈ 2.5

Welding of vessels

- Largest width of forgings/plates made by industry ≈ 4 m
- Plates to be welded for NuScale primary vessel: 4 + bottom and top heads
- Plates to be welded for LFR primary vessel: 1 + bottom head + lid
- Cost of welding:
  - inversely proportional to deposition rate
  - Proportional to square of wall thickness



Forging & welding of pressure vessel rings

- Forging & welding of a 12 m tall VVER-1200 vessel takes 36 months, including overlay weld of the vessel liner:
- https://www.youtube.com/watch?v=91yVhrSZ5jQ
- Forging & welding of a RITM-200 vessel takes 27 months:
- https://www.youtube.com/watch?v=v2eW6HHvZEg

Time & cost of welding LFR vessel

- Gas Metal Arc Welding suitable for SS316 to SS316 weld of vessel pieces

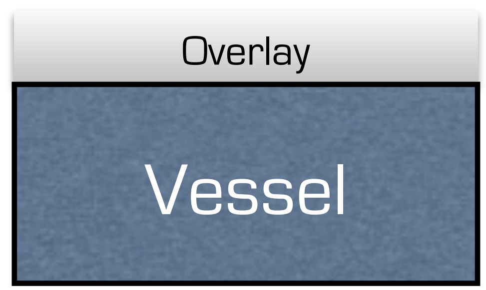
Item	Value
Deposition rate	3-6 kg/h
Weld volume	Weld length x area
Weld mass	Weld volume x density
Weld time	Weld mass / deposition rate
Welder's time	5/3 of weld time
Welder cost	€ 50/h
Total welding cost	5/3 of welder cost
Overheads	30-50% of direct cost

- Estimate time and cost for welding of the primary vessel of SEALER-55
- Assume 2 horisontal and 1 vertical welds & butt weld angle = 60°
- Vessel thickness: 40 mm. Vessel diameter: 5.0 m, Vertical weld length 4.0 m
- Filler density: 8000 kg/m^3

Time and cost for overlay welding of LFR vessel

- Alumina forming austenitic (AFA) or Fe-10Cr-4Al overlay weld of 3 mm thickness to be used for corrosion protection in LFRs
- Tungsten-Inert-Gas (TIG) welding of AFA tested at KTH.
- Laser welding of Fe-10Cr-4Al tested in China.

Item	Value
Deposition rate	**3 kg/h (TIG)**
Weld volume	**Weld thickness x area**
Weld mass	**Weld volume x density**
Weld time	**Weld mass / deposition rate**
Welder's time	**5/3 of weld time**
Welder cost	**€ 50/h**
Total welding cost	**5/3 of welder cost**
Overheads	**30-50% of direct cost**



- Estimate time and cost for AFA overlay welding of SEALER-55 primary vessel.
- Assume deposition rate of 3 kg/h

Fuel costs

- iPWRs: (www.uxc.com)
  - Market cost for 4.9% enriched UO_2: USD 2800/kg
  - Cost for fuel assembly manufacture: USD 250/kg of uranium
- HTRs with 9% enriched UO_2 fuel:
  - Market cost for 9% enriched UO_2: USD 5500/kg
  - U-Battery estimate for TRISO fuel: USD 15 000/kg of uranium
- LFRs with 12% enriched UN fuel:
  - Market cost for 12% enriched UF_6: USD 7500/kg
  - Cost for building UN pellet fuel factory: USD 200 M (Westinghouse)
  - Annual CAPEX for factory (WACC = 6%): USD 17 M
  - Production capacity: 600 t/year yields specific CAPEX ≈ USD 30/kg

"Indirect services costs"

- ≈ 35% of total cost of construction of PWRs in the US (!)
- Major reason for cost overruns

- Costs for equipment and construction facilities (30%)
- Construction supervision (30%)
- Commissioning and test runs (≈ 1%)
- Design services (35%)
- Project and construction management (≈ 4%)

Overruns in indirect cost expenditures

- Items of non-legal character found to dominate cost overruns:

- Lack of complete design before start of construction
- First-of-a-kind (FOAK) design
- Delays and rework due to supply chain
- Long construction schedule
- Insufficient oversight by owner

- Recent examples of quality problems in supply chain: Concrete pours (Olkiluoto, Flammanville), Vessel welds (Flammanville), pump functionality (Sanmen), pump failure (Olkiluoto).
- Canadian rule of thumb: 9% of budget should be spent on project management for success to be ensured.

ISO-19443

Standards All about ISO News Taking part Store EN ☰ MENU

ISO

ICS › 03 › 03.120 › 03.120.10

ISO 19443:2018

Quality management systems — Specific requirements for the application of ISO 9001:2015 by organizations in the supply chain of the nuclear energy sector supplying products and services important to nuclear safety (ITNS)

- New standard for nuclear industry management
- Aimed at addressing quality problems observed in recent new-build, in particular related to project management.

[Abstract of ISO-19443 standard]

Operational staff at US LWR plants with one or two units on site (IAEA)

Category	1 unit	2 unit	Scales
Manager's office			
Security	120	130	Constant
Administration	30	50	> Root
Training	30	40	< Root
Management	30	35	Constant
Others	120	120	Constant
Total	330	375	

Category	1 unit	2 unit	Scales
Maintenance			
Crafts	120	185	Root
Annualised revision	50	100	Linear
Engineering	40	55	Root
Support	20	40	Linear
Total	230	380	

Category	1 unit	2 unit	Scales
Operations			
Shift operations	75	120	Root
Engineering	30	45	Root
Support	20	20	Constant
Total	125	185	

Category	1 unit	2 unit	Scales
Technical support			
Technicians	20	30	Root
Engineering	20	30	Root
Warehouse	10	15	Root
Total	50	75	

One unit plant full time equivalent staff: ≈ **730/GWe** Two unit plant: **≈ 500 FTE/GWe**

Waste management & decommissioning

- In Sweden, utilities co-own SKB, the nuclear waste management company.
- In Finland & Canada, Posiva and NWMO play a similar role
- Annual fees are set aside to fund
  - Interim storage of spent fuel in CLAB
  - Disposal of low- and intermediate level waste from operations and decommissioning
  - Deep geological disposal of spent fuel in Forsmark
  - Decommissioning of reactors
- SSM (the regulator) determines fee based on budget made by SKB
- Fee varies from 3 €/MWh for Forsmark to 6 €/MWh for Oskarshamn

Levelised cost of electricity (LCOE)

- LCOE does **not** include
- Cost of transmission
- Profits of power utility
- LCOE includes
- Cost of capital
- Cost of operation and maintenance
- Fees for waste management and decommissioning
- Discounted value of future revenues from operation

CAPEX: example evaluation

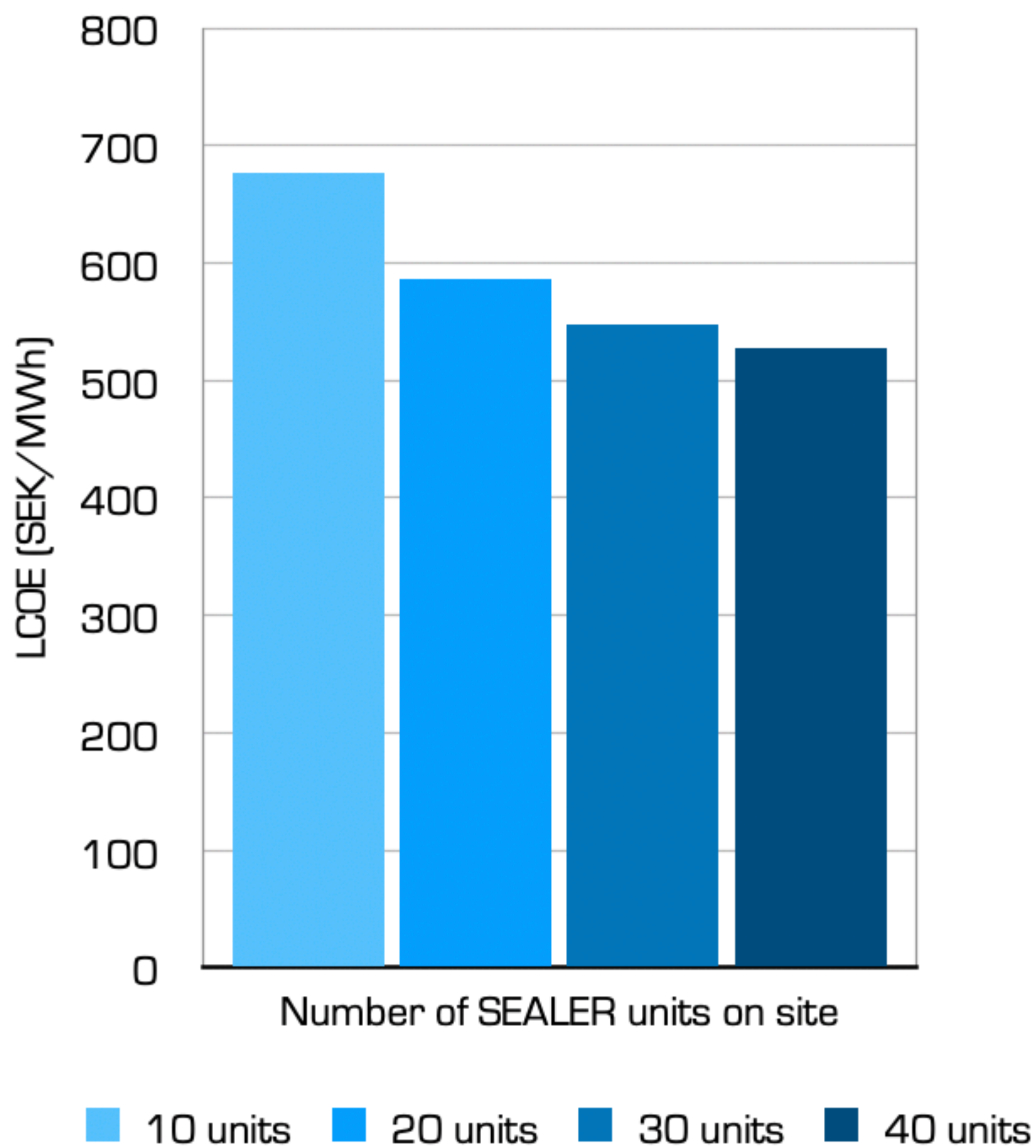
Account	Label	100 MWe iPWR, 3 y duration to build, 25 y economic life Cost (MUSD)		
10	Pre-construction	10		
20	Direct construction	160		
30	Indirect services	80	50% of direct cost	SMR benefit!
40	Owner's costs	40		
50	Supplementary costs	5		
60	Financing during construction	27	**9% of overnight cost**	SMR benefit!
	Cost of construction	**322**	**WACC = 6%**	
	CAPEX	**25**	$$CAPEX = Cost_{construction} \times \frac{WACC}{1 - \frac{1}{(1+WACC)^n}}$$	

Annuity factor

OPEX and LCOE: example evaluation

Label	100 MWe iPWR, single unit Cost (MUSD)		
Staff	12	1000 staff/GWe	0.12 MUSD/staff/y
Maintenance	13	4% of construction	Rule of thumb
Fuel	5		1200 USD/kg
Waste fee	4	5 USD/MWh	90% availability
OPEX	**34**		
CAPEX	**25**		
CAPEX + OPEX	**59**		
LCOE (USD/MWh)	**74**	0.8 GWh	90% availability

LCOE as function of number of co-located units



- LCOE drops as number of co-located units increases.
- Why?
- Fewer than 10 SEALER units on a single site not expected to be commercially profitable on nordic electricity market.

Final project definition

- Design a small reactor unit with an electrical power of 100/200 MW and enriched uranium oxide or nitride fuel.
- Calculate reactivity swing for a fuel average burn-up of 50 GWd/ton and determine the control rod configuration so that the maximum control rod worth is less than 0.5$. Reactivity losses are to be minimized by use of a burnable poison (iPWRs & HTRs) or by optimization of ^{235}U fraction in the fuel (LFRs).
- Calculate the fuel Doppler coefficient and moderator/coolant temperature coefficient (iPWRs, LFRs, HTRs), as well as fuel axial expansion coefficient and diagrid radial expansion coefficient for LFRs.
- Determine the radius of the emergency planning zone, assuming 100% release of xenon and 0.1% release of iodine in a severe accident occurring for a core average burn-up of 50 GWd/ton. The dose acceptance criterion is 20 mSv.
- Estimate capital cost and operational cost for a plant with 8 units, based on scaling from literature data. Estimate the LCOE for this 8-unit plant assuming an economic life of 25 years and 90% availability.