ARUP

Tunnel Thermal Heat Recovery

Compact Linear Collider – Progress Update

22.04.2022

ARUP

Agenda

1. Update on Technical Design Feasibility (Arup)
2. Update on Technical Demand Feasibility (Arup)
3. Update on Whole life cycle carbon assessment (Arup)
4. Q&A (CERN and Arup)
5. Agree final deliverables (CERN and Arup)

Technical Design Feasibility

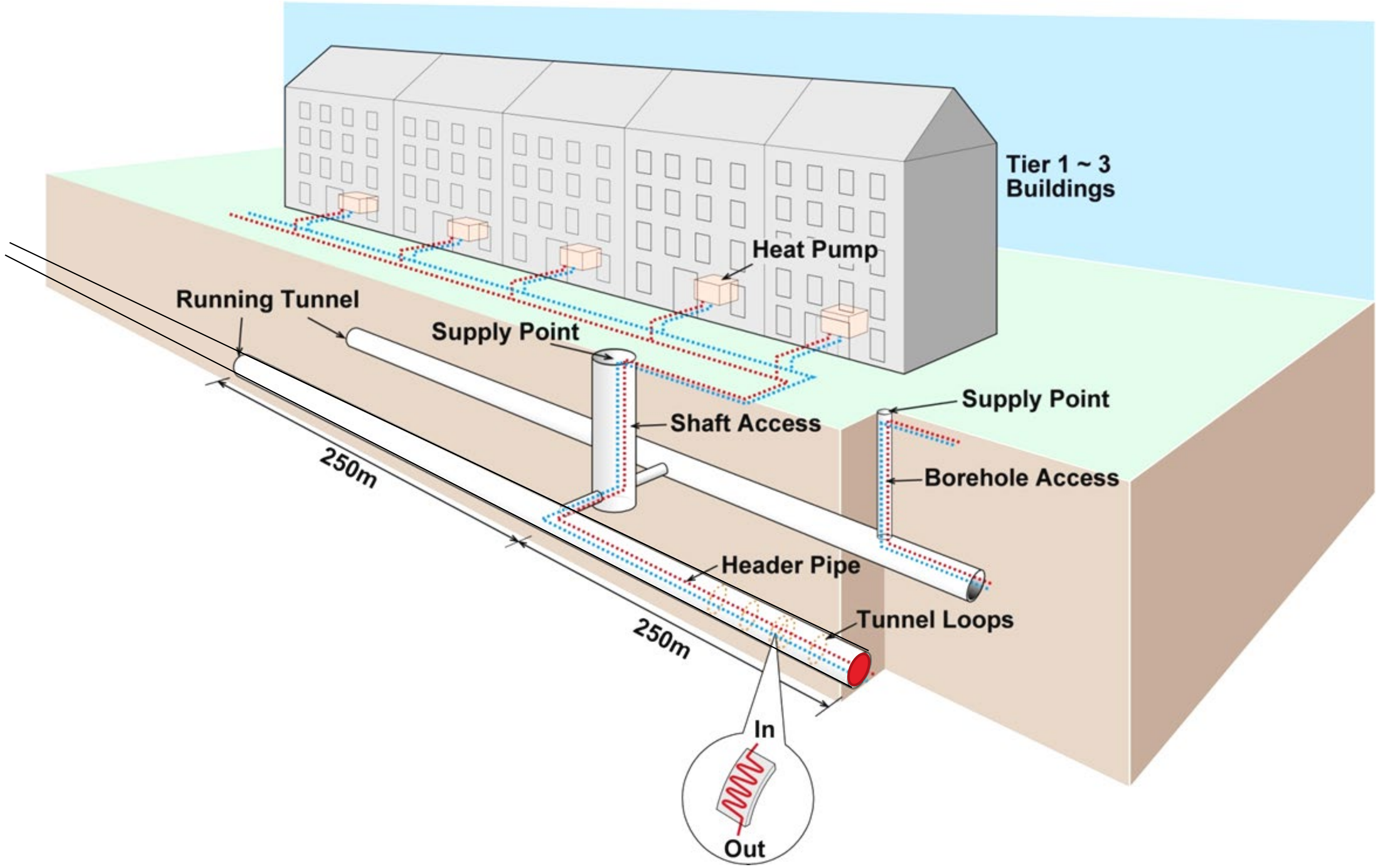
Alex Chen

ARUP

ARUP

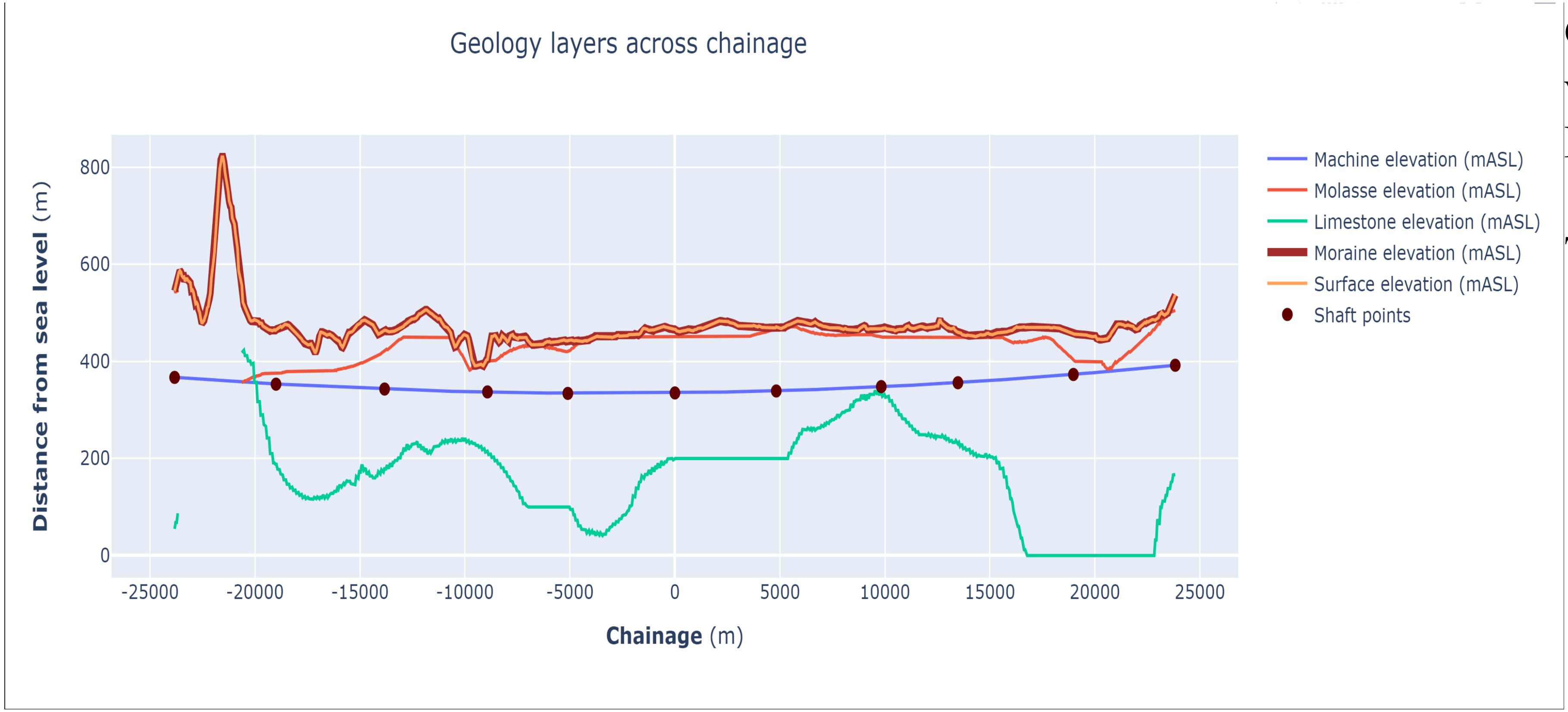
Crossrail Design

Tunnel energy liner, 2009-12



- 11 km tunnels
- Twin tunnels
- 8 Stations and 5 shafts
- Heat extracted from tunnel air and ground (In July 2008 temperature in the Tube reached 47˚C)
- Activated tunnel length 500m from an access point, one side or 2 sides
- Delivery temperature boosted by heat pump
- Heat distributed by district heating operator

Geology and Tunnel Alignment



Geology: Molasse Fm within France-Geneva Molasse Basin

Tunnel Depth: 124 mbgl

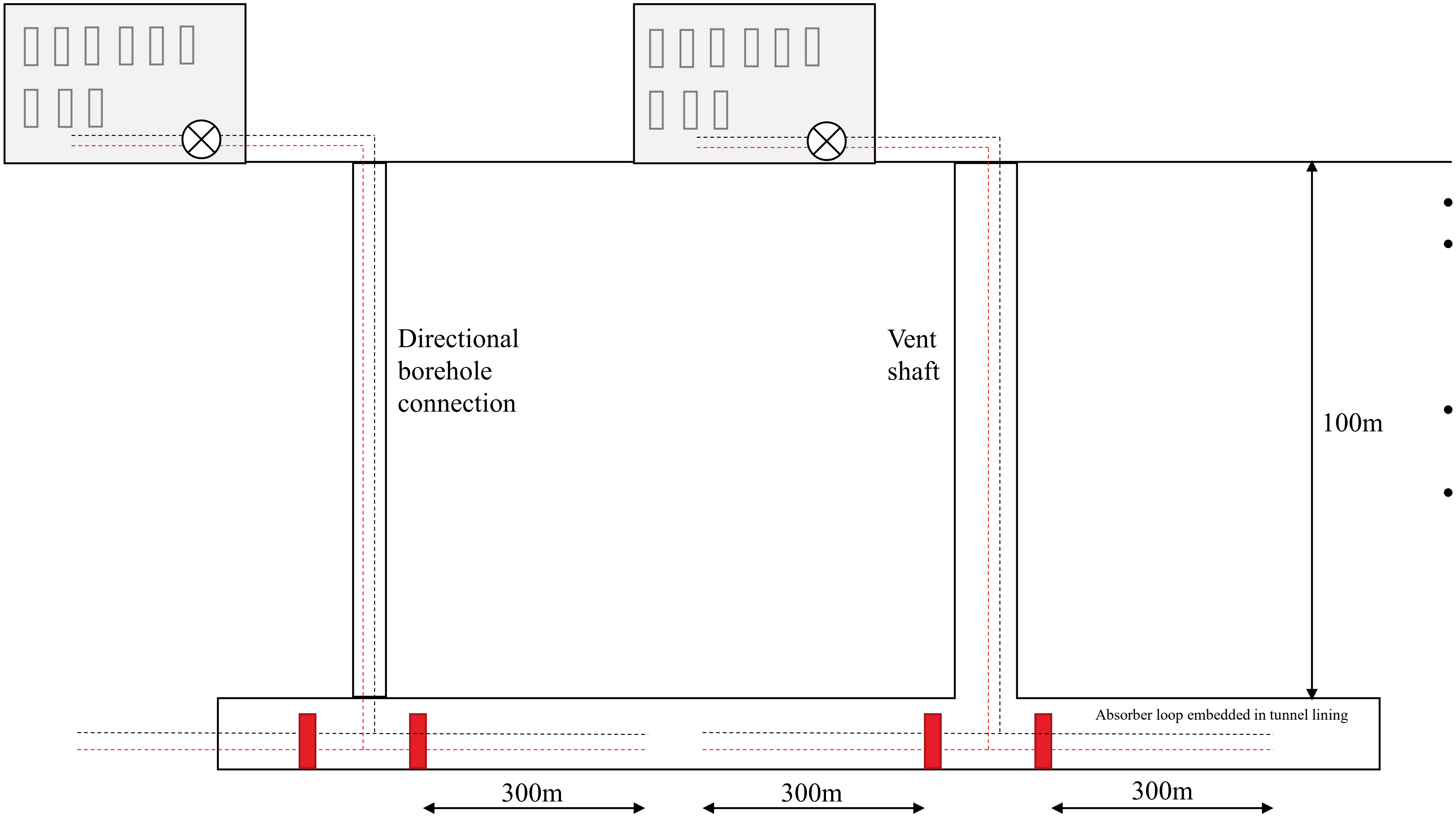
ARUP

CLIC vs Crossrail

Parameters	CLIC	Crossrail	References	Comments
Tunnel diameter (ID)	5.6m typical for the main tunnel (up to 8m)	6.2m	Ref-7, 8	
Segment number	NA	7 + keystone		
segment thickness (m)	0.3 ?	0.3		
Segment concrete	fibre or steel?	fibre reinforced		
Tunnel depth (m)	124m (average)	20 to 30m	Ref-2	
tunnel length (km)	47.7	22	Ref-3	
Service tunnel liner	SCL?	NA		info requested
Geology at tunnel level	mostly within the Molasse deposit, Swiss Molasse Basin	London Clay, London Basin	Ref-2	
Lithology	conglomerates, mudstone, sandstone, marl	overconsolidated clay silt	Ref-1	assumed Molasse is saturated
Geothermal Gradient	35C to 40 C/km		Ref-5, Fig 1, No major aquifer at or above tunnel depth	
Ambient temperature at tunnel	14C to 15C	14.8C		assuming CLIC ground temp is 10C at 10m depth
Ground thermal conductivity (W/m-K)	2.1	1.8	Ref-5, 7, 9	weak relevance to site
Ground thermal capacity (J/kg-K)	900 - 1200	1000	Ref-7, 9	
Concrete thermal capacity (J/kg-K)	700	700	Ref-7	volumetric Svc = 2300 kJ/m3-K
Tunnel air temperature	Constant, 23C and 28C	14C to 30C	CERN-1, Table 1	
Geothermal heat flow (W/m^2)	0.07	0.06		
Hydraulic gradient	v low	v low		assumed, ignored
Hydraulic conductivity (m/s)	low	v low		assumed , ignored
Energy sources	surrounding rocks for heating and cooling	surrounding rocks and warmed tunnel air, for heating only		
Ground heat exchanger loop size	20mm ID, 25mm OD	20mm ID, 25mm OD		assumed

ARUP

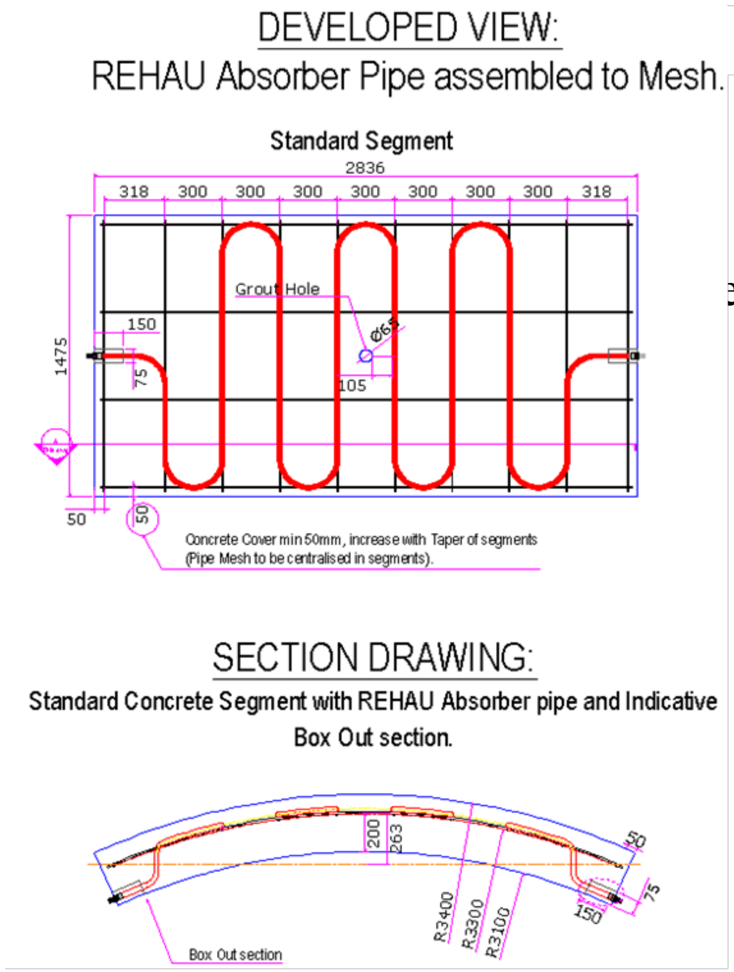
CLIC Conceptual design

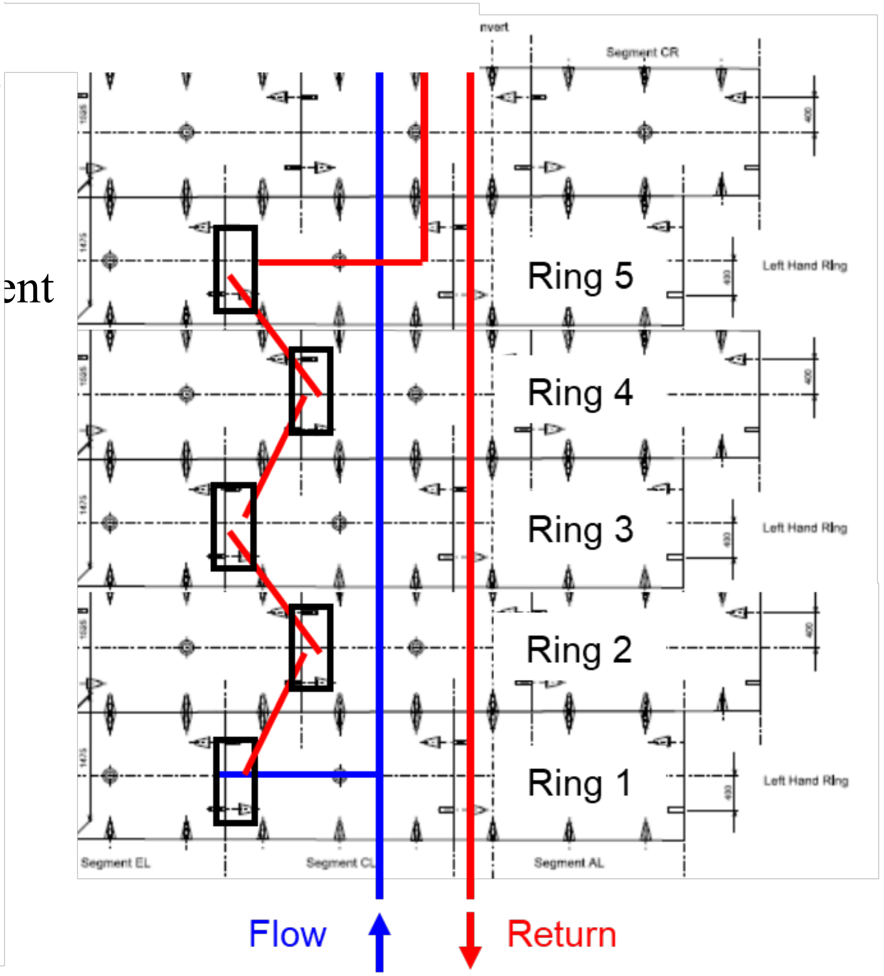


- Tunnel at 124m depth
- Heat exchangers to connect loop circuitry in the tunnel and heat pump at surface
- 300m length of tunnel forms one circuit loop
- 2 or more circuit loop on one side or 2 sides at the shaft/borehole entry point

Pipe arrangement in Pre-cast segment

Crossrail design

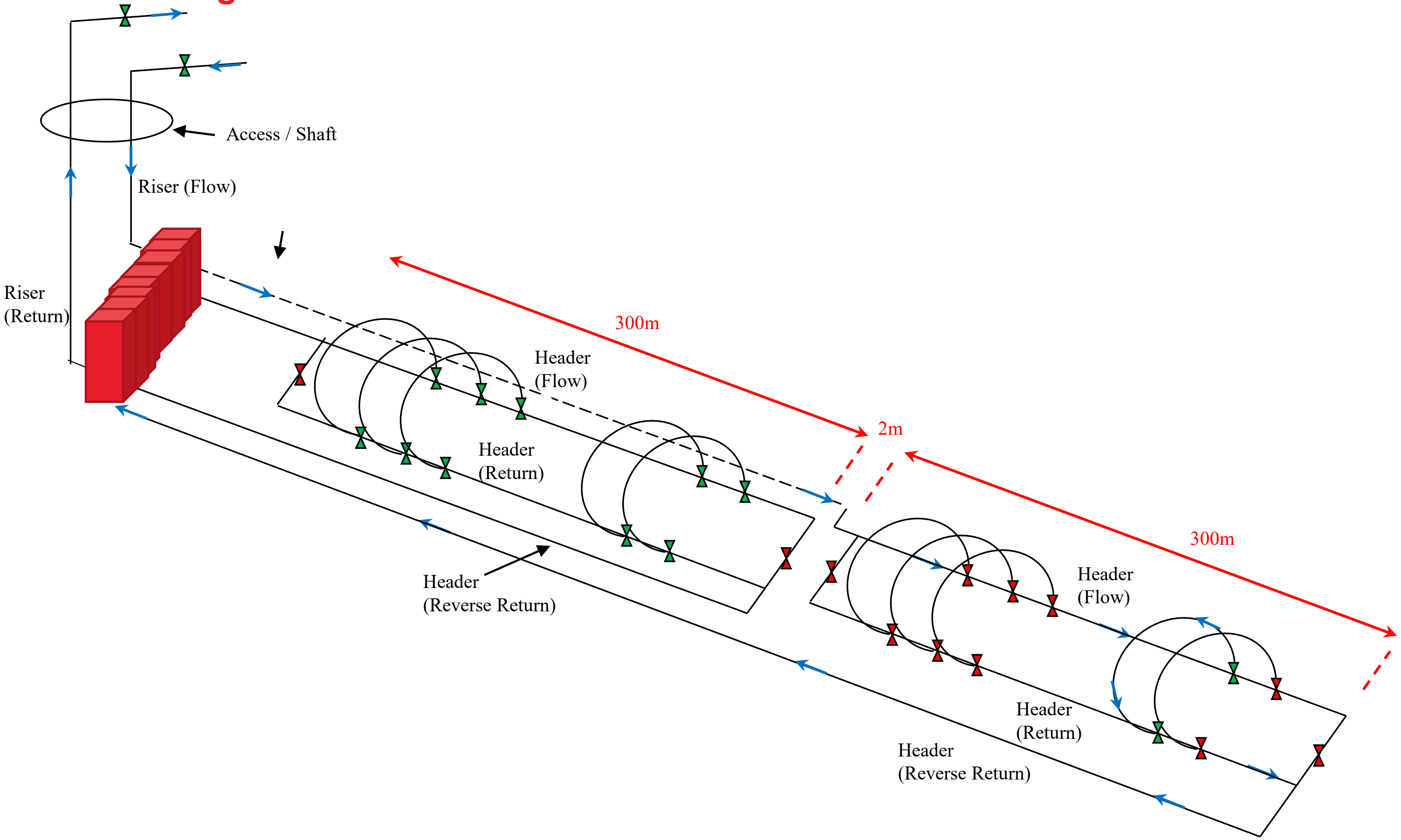




ARUP

Circuit loop in tunnel (Shaft access)

Crossrail design

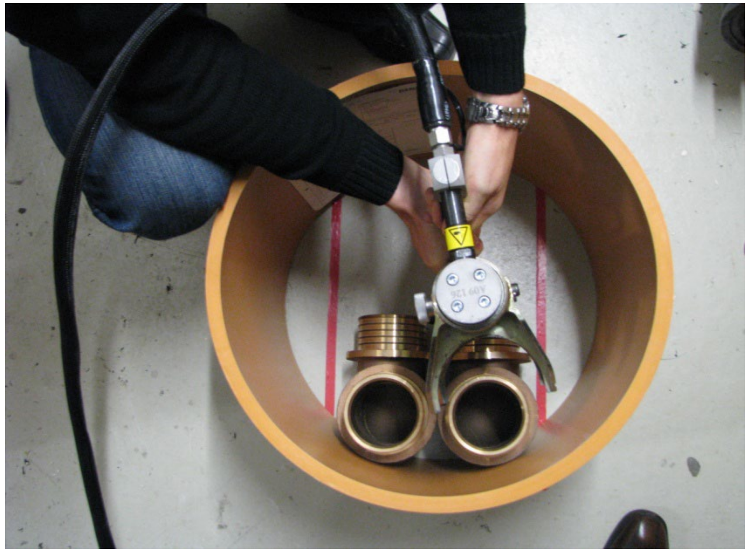


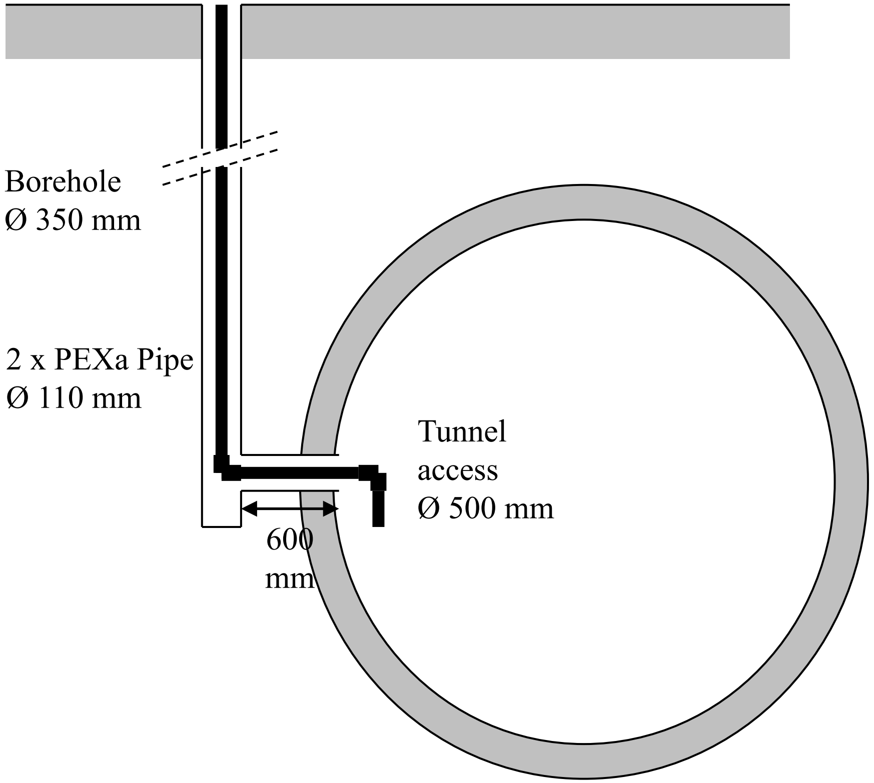
ARUP

Surface connection by borehole

Crossrail design

- 110 mm flow & return pipes
- 500 mm opening

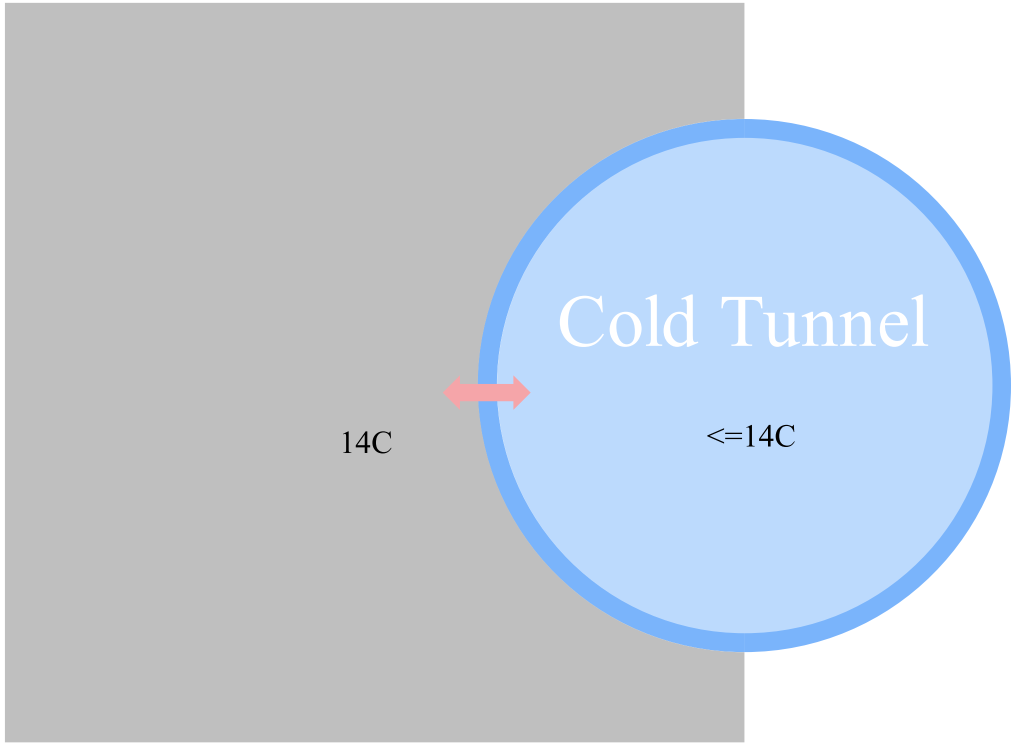




ARUP

Cold Tunnel

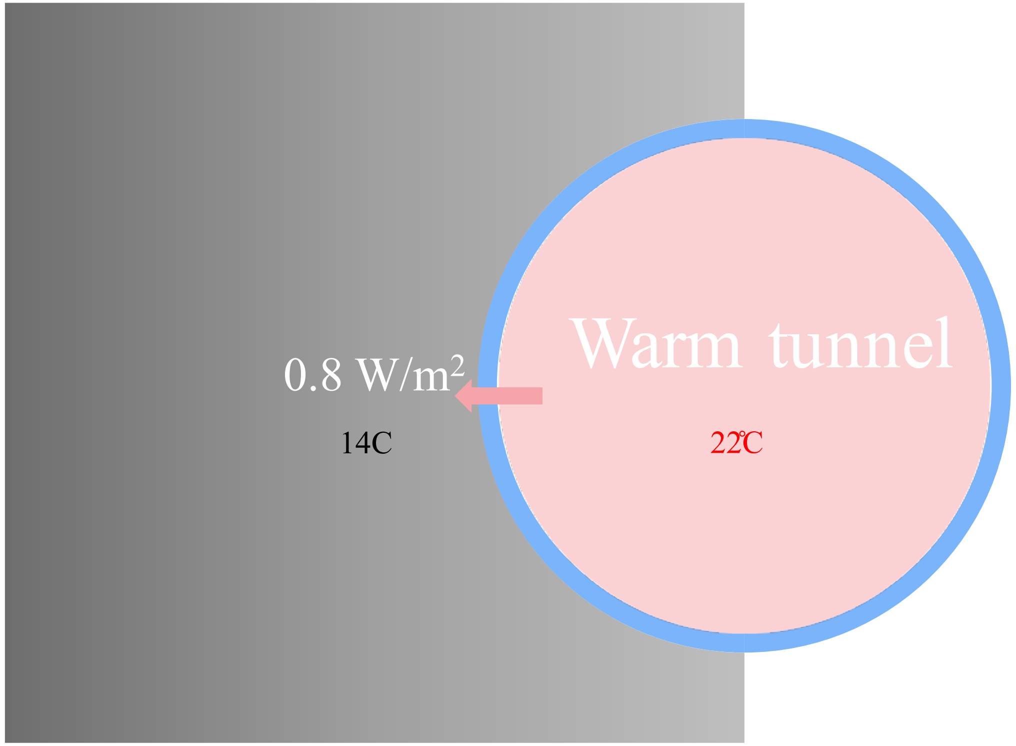
Short road tunnel, rail tunnel, cold climate, natural ventilation



ARUP

Warm Tunnel

Metro trunnel, long road tunnel, long rail tunnel, sewer



$$\dot{q} = \left[\frac{2\pi k}{\cosh^{-1}(d/r)}\right] U_o \quad \text{watts/m}$$

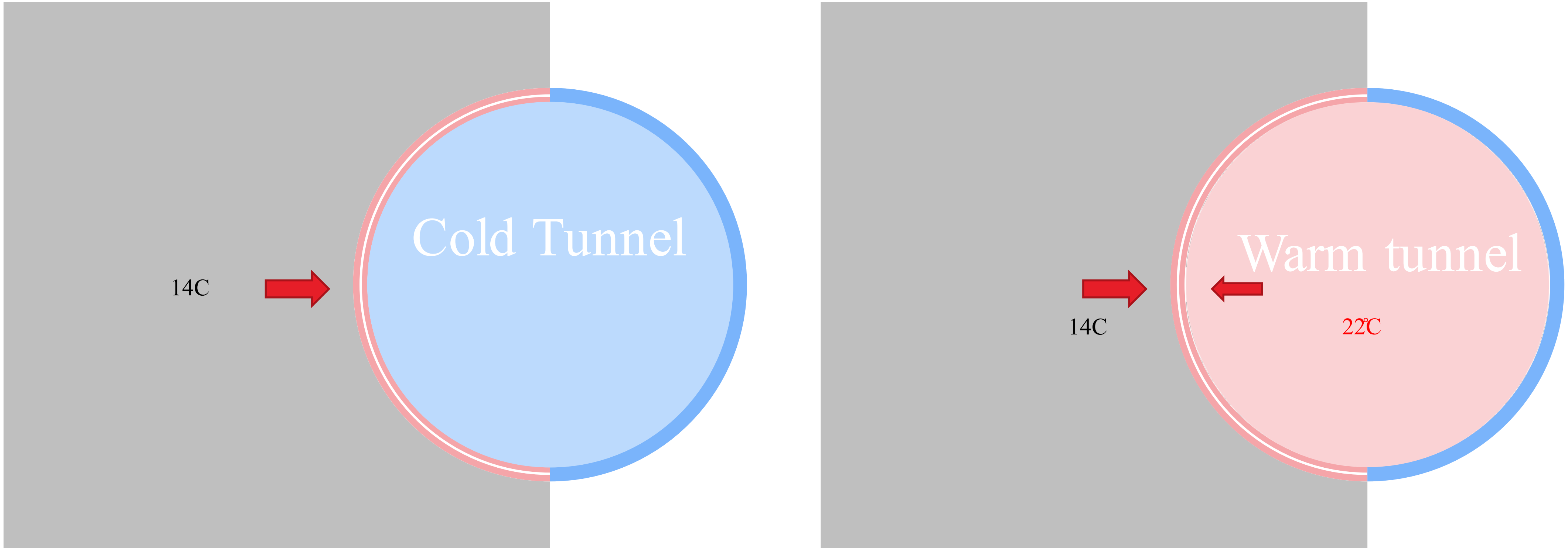
d= tunnel depth (m)
r= tunnel radius (m)
k= thermal conductivity of soil and liner(W/m-K)
U_0= temperature diff of tunnel air and soil (K)
$\cosh^{-1}$(x)= inverse of cosh(x)

Bowden, 2003

ARUP

CLIC Tunnel

A Cold or Warm tunnel?



ARUP

Thermal Tunnel (Cold Tunnel)

Tunnel lining – ground temperatures for 4 scenarios

- Heat extraction and rejection rate: 10 W/m²
- Energy from tunnel air not considered
- Heat rejection considered

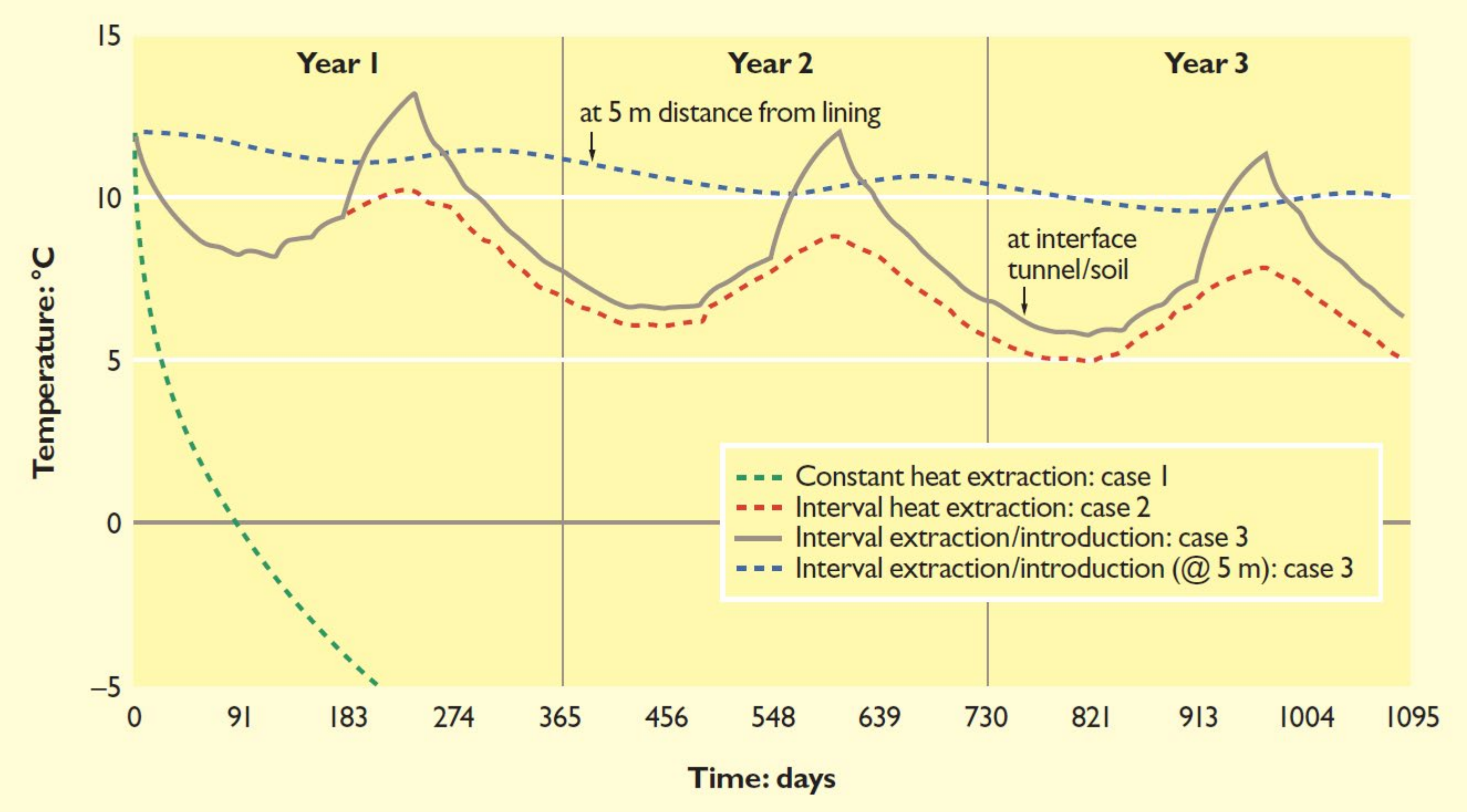


Figure 5. Modelled ground temperature for different operations of the tunnel heat-exchange system (all at lining–ground interface except where shown)

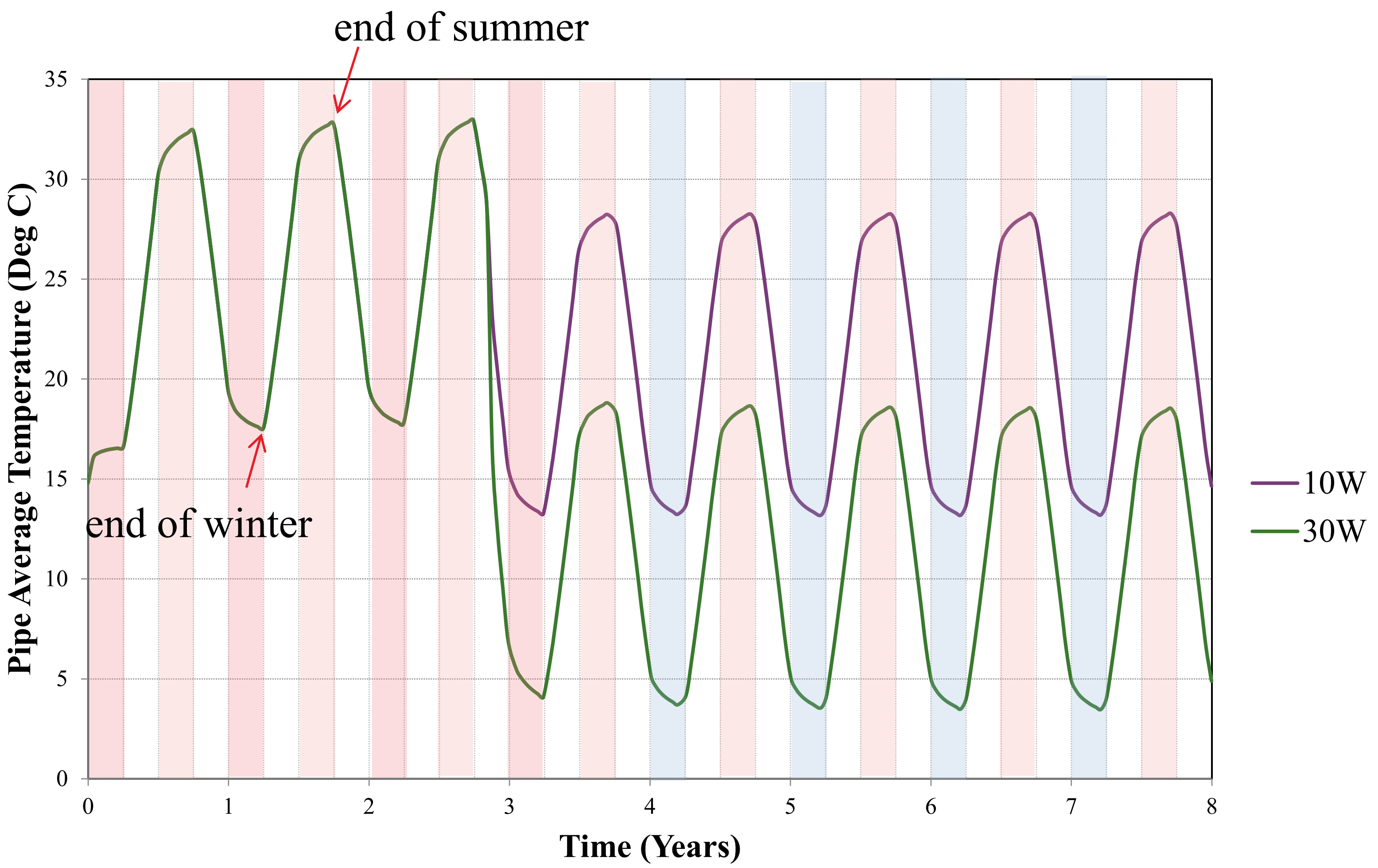
Norbert Pralle, Jan Niklas Franzius, 2011

ARUP

Thermal Tunnel (Warm Tunnel)

Average pipe temperatures, studies for Crossrail design

- Heat extraction rates:
  - 10 W/m^2
  - 30 W/m^2
- Heat from warmed air considered
- No heat rejection (i.e. no building cooling demand)



Nicholson, D 2014

ARUP

Thermal Tunnel – energy output

600m tunnel length

Parameters	Unit	heat extraction for 1200hr per year	heat extraction for 1200hr/yr. and heat rejection for 60hr/yr. and warmed tunnel air	heat extraction for 1200hr/yr. and heat rejection for 60hr/yr. and warmed tunnel air2	heat extraction for 1200hr/yr. and eat rejection for 900hr/yr., plus continuously warmed air	Note
heat extraction rate	W/m^2	10	15	20	30	based on LS-DYNA and FTSC simulations
tunnel diameter	m	5.6	5.6	5.6	5.6	CERN
thermally activated tunnel length	m	600				hydraulic loss and pipe pressure rating
total tunnel area at each access point	m^2	10,556				
heat output at accessible point	kW	106	158	211	317	
COP for heating	-	3.5				Assumed
heat delivered to buildings	kW	148	222	296	443	

ARUP

Thermal tunnel vs GSHP borehole

How thermal tunnel compares with closed loop boreholes

600m long tunnel, 10 W/m^2 = 105 kW

1nr 100m deep closed loop borehole = 30 W/m x 100m = 3 kW

1 nr 200m closed loop borehole = 6 kW

Thermal tunnel 600m ~ 35nr 100m deep boreholes

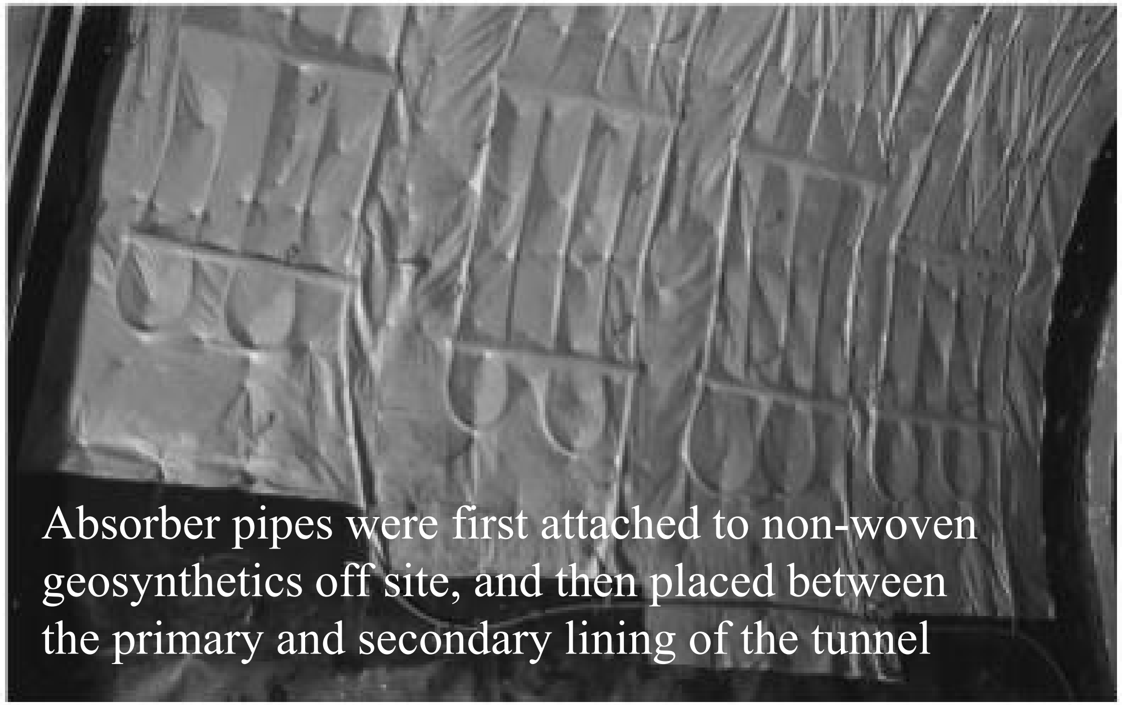
ARUP

SCL thermal tunnel

Other options, SCL tunnel?

Fig. 2. Installation of tunnel lining GHEs at Linchang tunnel.

Linchang Tunnel

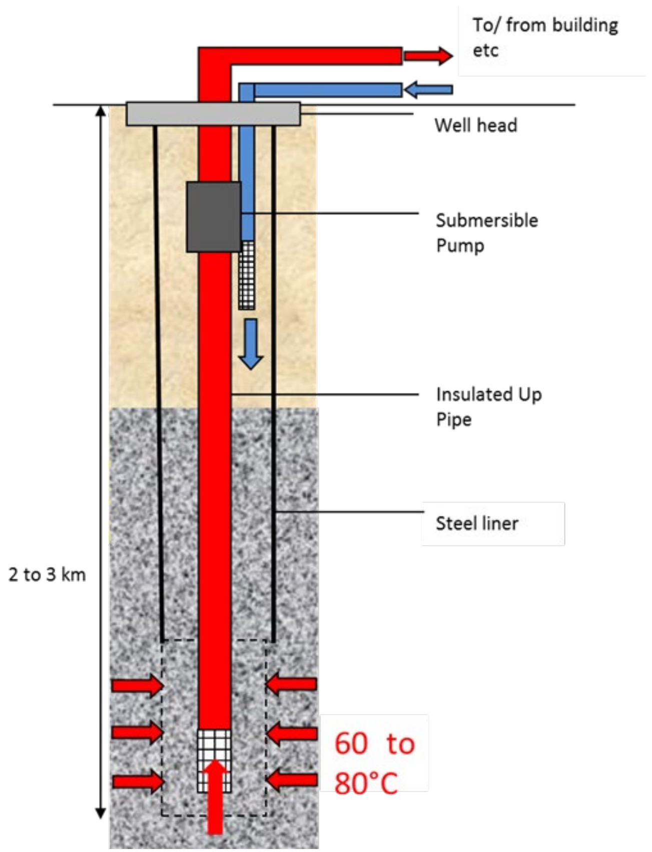


LT22 of the Lainzer tunnel, Adam, D. & Markiewicz, R. 2009.

ARUP

Deep geothermal single well option

DGSW technology to provide district heating



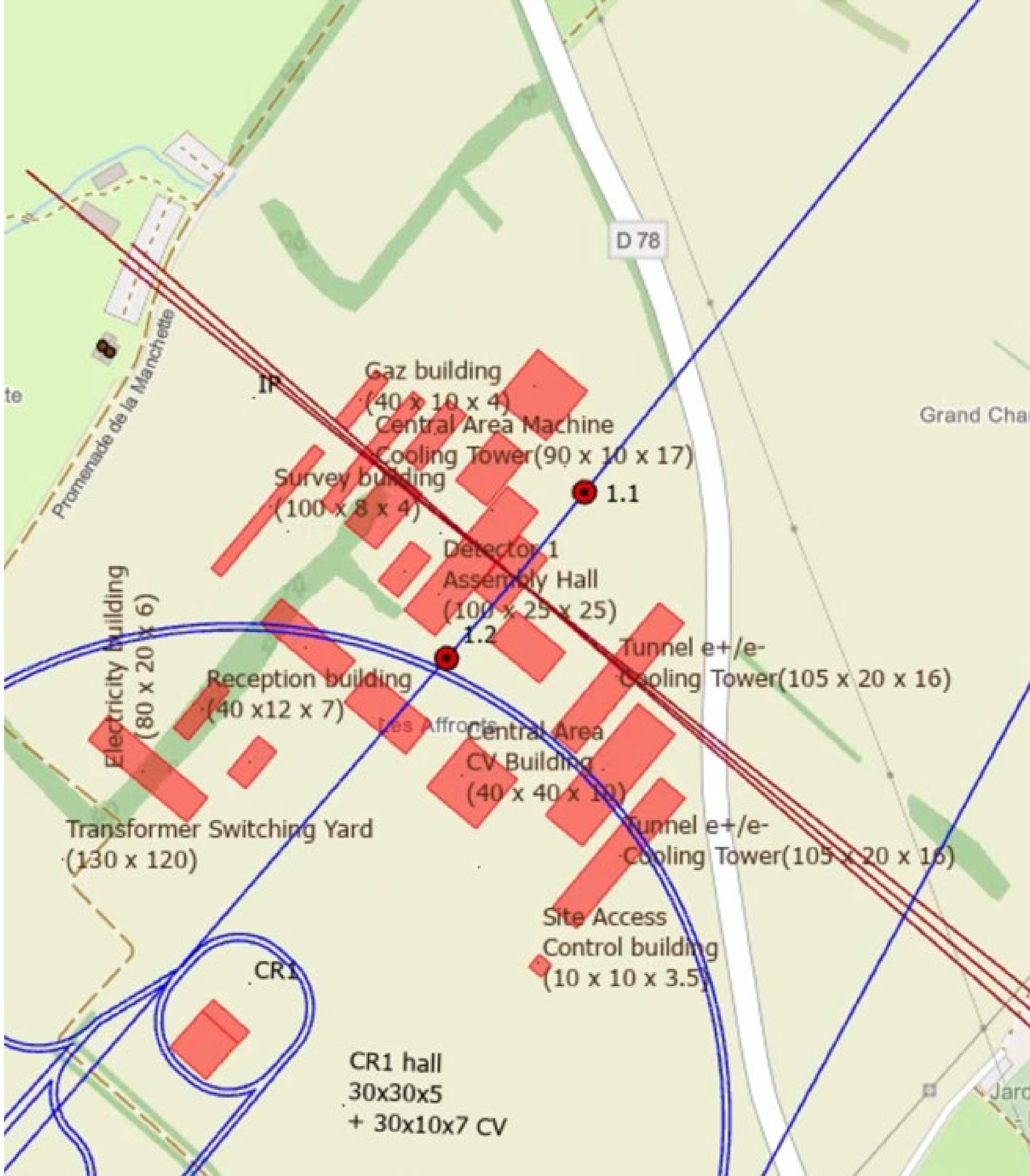
Rosemanowes Quarry DGSW, England, 400kW of heat with bleed flow of 3 l/s

- A single vertical well is drilled to depths of 2 to 3 km and a steel casing installed over the upper section
- A polypropylene pipeline is installed inside the well and extends to near the base of the well. A submersible pump is installed within this pipeline at a shallow depth
- A flexible hose is installed inside the vertical well to introduce water from the surface
- Groundwater at depth is heated by the surrounding geothermal gradient.
- The heated water within the well is drawn-up to the well-head through the polypropylene pipeline via the submersible pump.
- Heat is extracted from the water via a heat exchanger where the heat is then delivered to an end user via an interface unit.
- Cooled water is returned to the well and sinks down by gravity. The circulation of water is an efficient process as the cooler water drops and warmer water rises in a convection current.

Technical Demand Feasibility

James Mercia

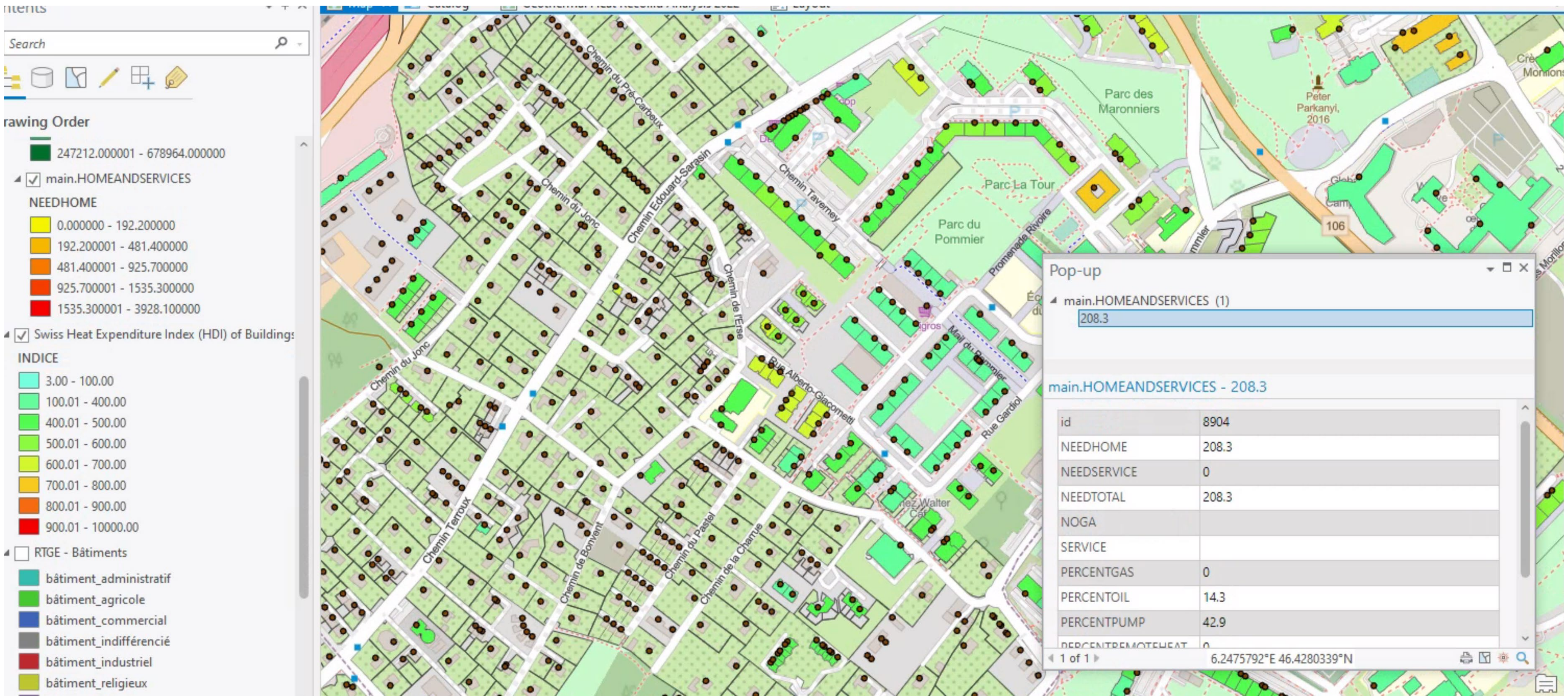
- Identifying potential surface building and infrastructure beneficiaries
- A review of open data sources to support analysis
- Demand allocated based on available energy resource
- Quantification of heat CO_2 decarbonation reduction



ARUP

Open data available for demand analysis

SITG, Swiss Federal Office of Energy and French Environmental Agency

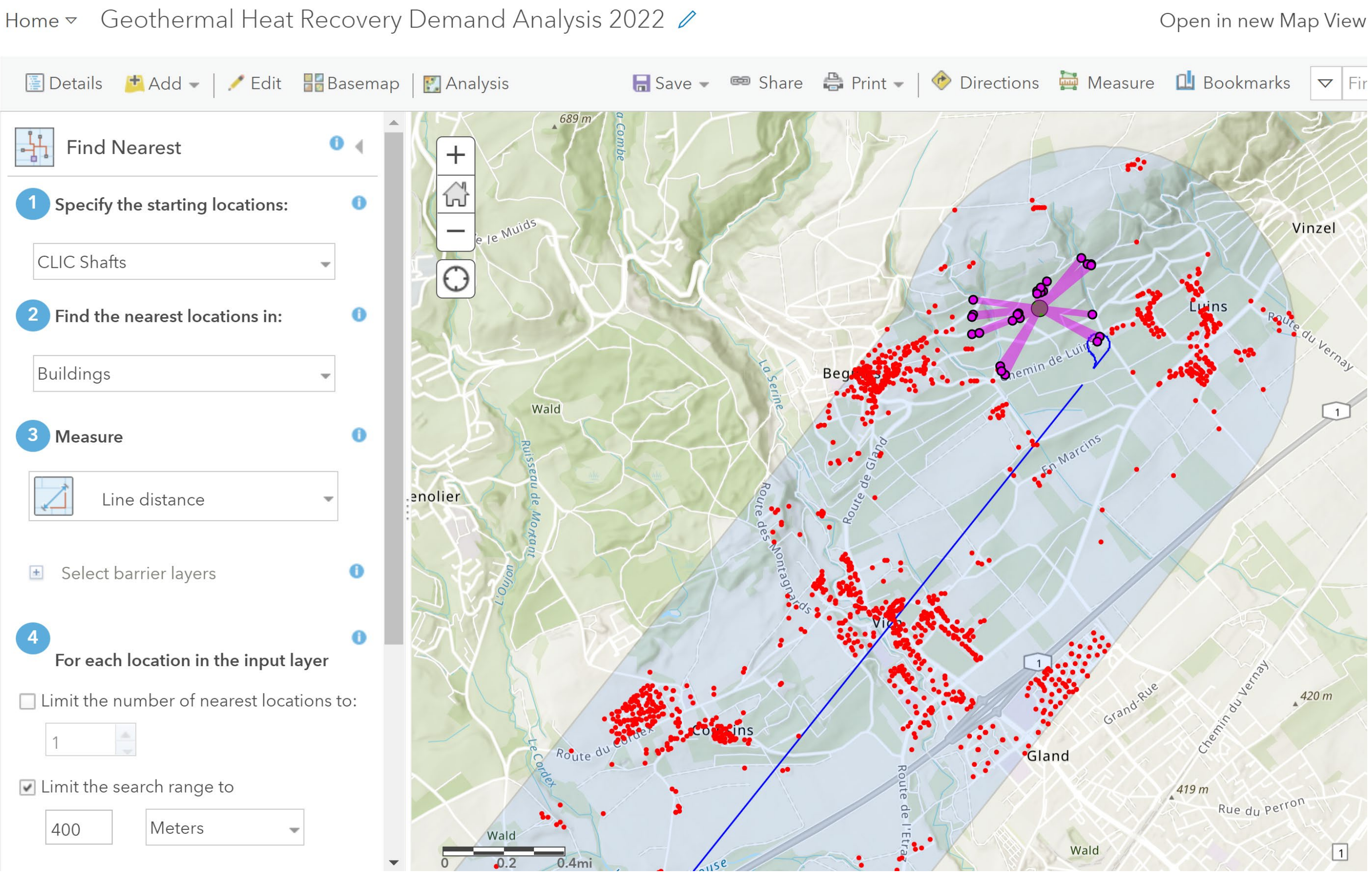


ARUP

Demand allocation

A tool to facilitate planning for an evolving design

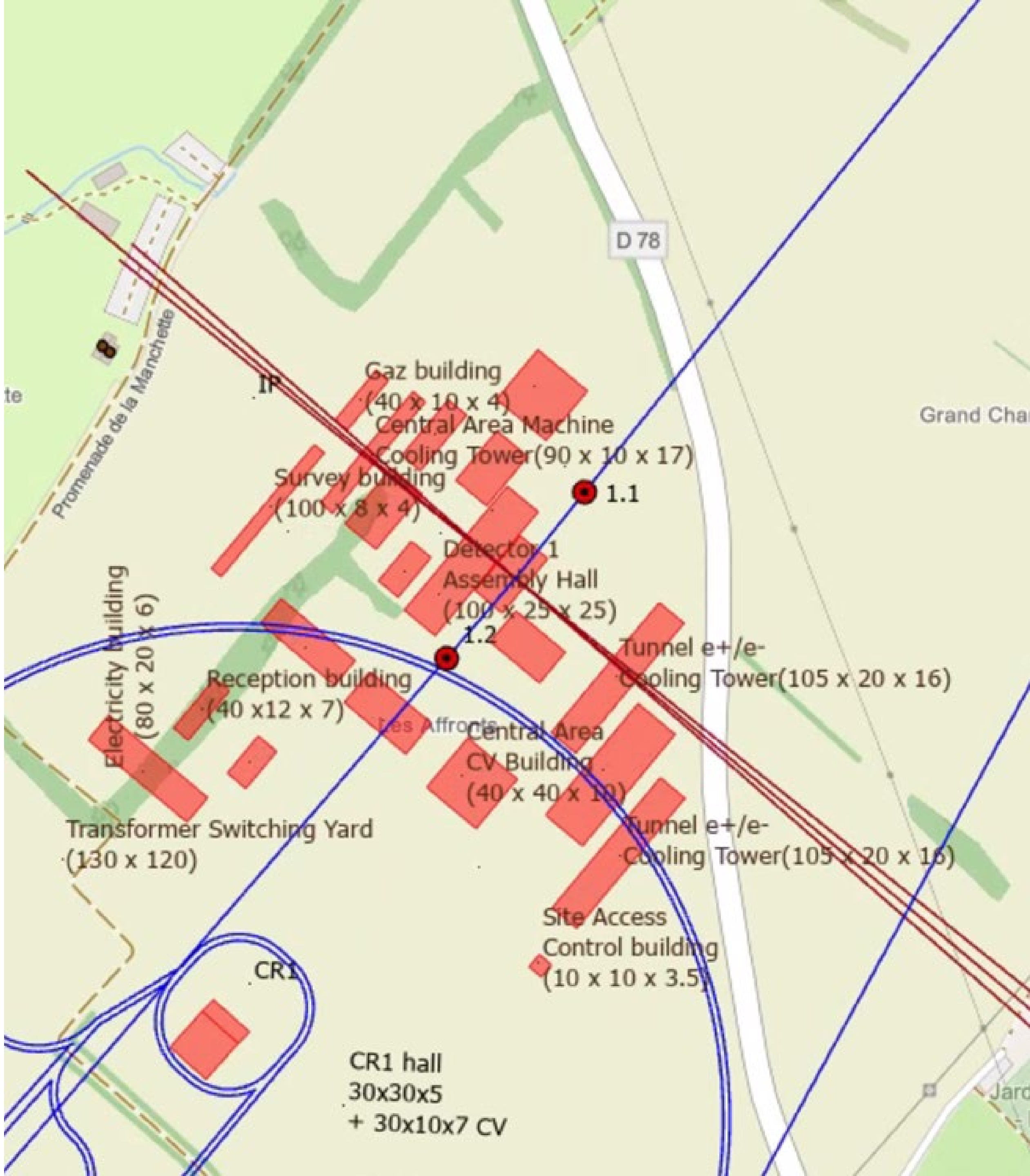
- Inputs:
  - Shaft locations
  - Buildings
  - Energy resource
  - Energy demand
- Output:
  - Allocated demand of heating/cooling needs to buildings



Technical Demand Feasibility

James Mercia

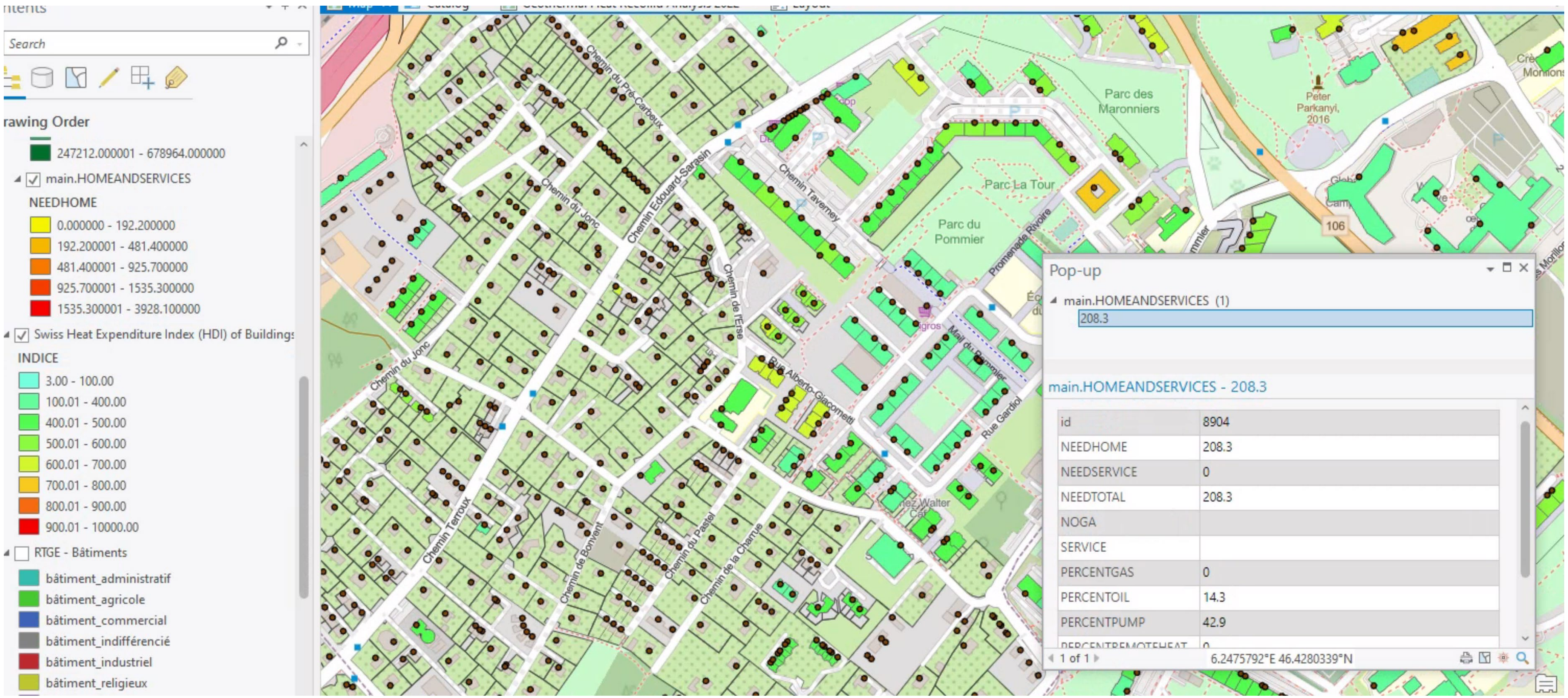
- Identifying potential surface building and infrastructure beneficiaries
- A review of open data sources to support analysis
- Demand allocated based on available energy resource
- Quantification of heat CO2 decarbonation reduction



ARUP

Open data available for demand analysis

SITG, Swiss Federal Office of Energy and French Environmental Agency

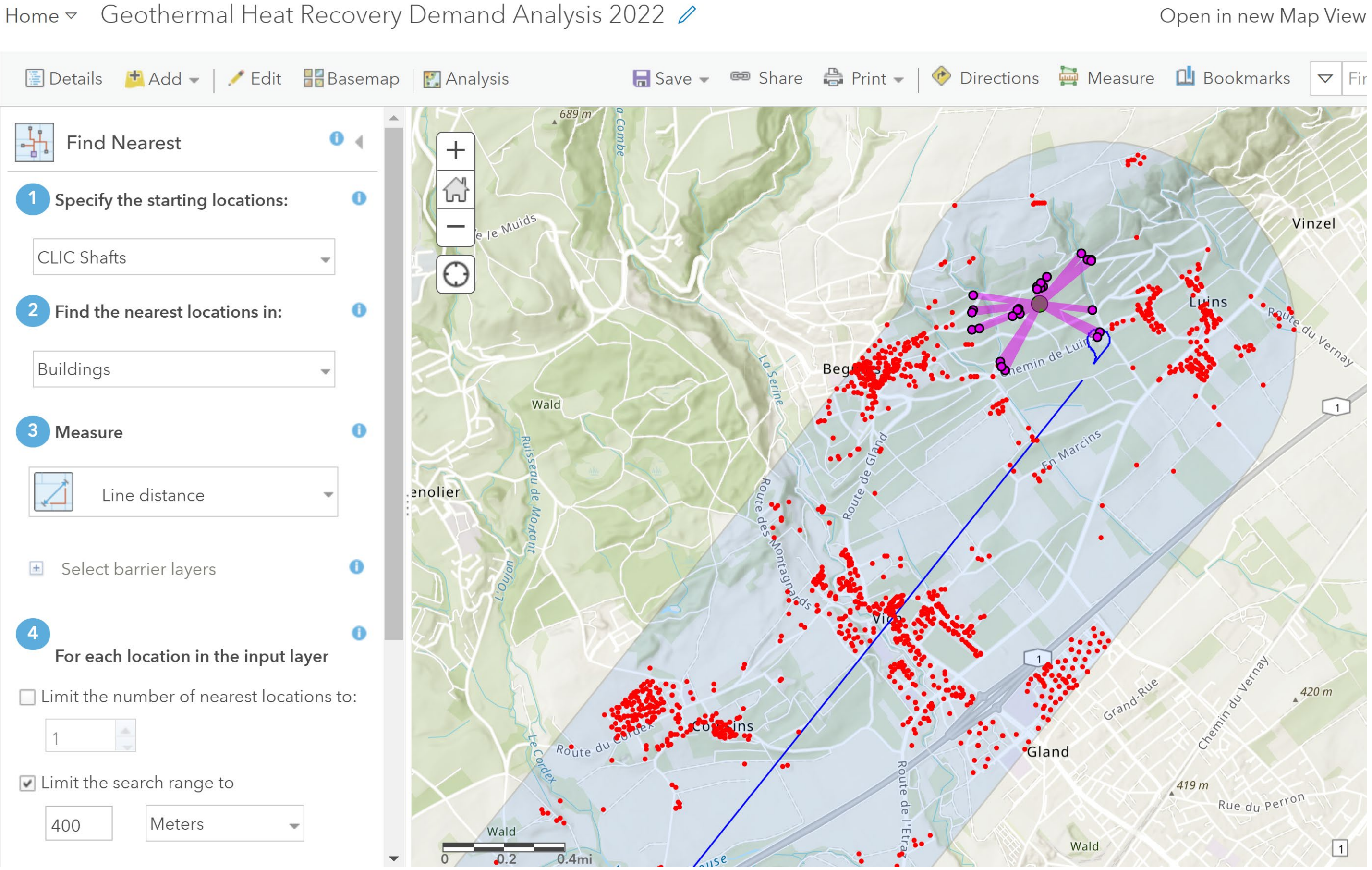


ARUP

Demand allocation

A tool to facilitate planning for an evolving design

- Inputs:
  - Shaft locations
  - Buildings
  - Energy resource
  - Energy demand
- Output:
  - Allocated demand of heating/cooling needs to buildings



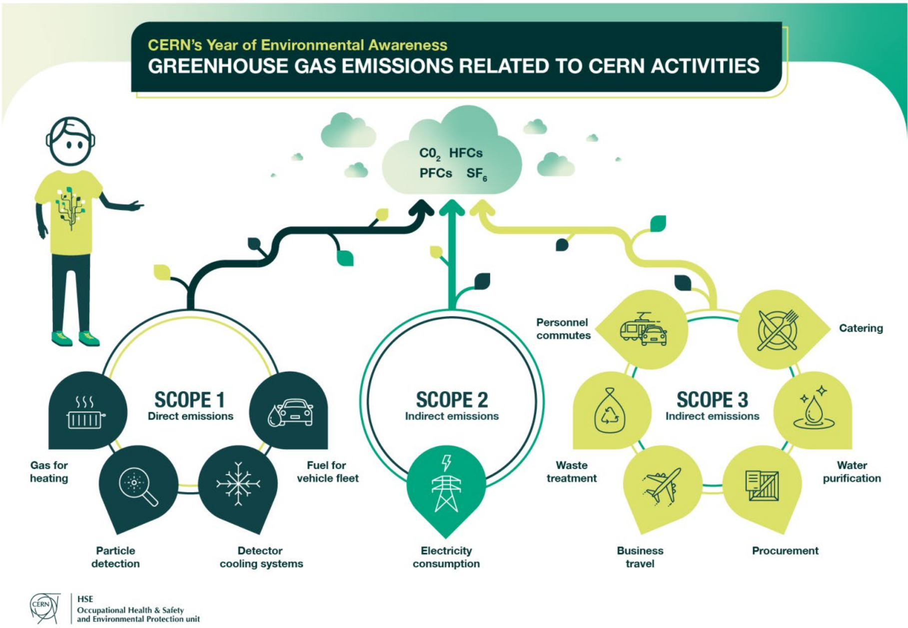
Whole Life Cycle Carbon

ARUP

Reihaneh Hafizi

Why be ambitious on Co2e reductions?

- Under a new law agreed between member states and the EU Parliament, the bloc will cut carbon emissions by at least 55% by 2030, compared with 1990 levels.
- CERN's immediate target is to reduce direct emissions by 28% by the end of 2024 (baseline year: 2018).



Reference:
CERN Environment Report 2019-2020

ARUP

Whole life cycle carbon assessment

Tunnel Asset (including access shafts)	length	internal diameter	lining thickness	invert concrete fill	separation wall	deck	CEM1 C35/45	70% GGBS C35/45	reduction in embodied carbon	
	km	m	m	m^2	m^2	m^2	tonnes CO_2e			
380GeV Drive Beam machine	12.1	5.6	0.4	4.8	0	0	60,000	26,000	57%	34,000
380 GeV Klystron machine	11.5	10	0.5	15.05	8.54	4.5	201,000	85,000	58%	116,000
1.5 TeV machine	29.6	5.6	0.4	4.8	0	0	146,000	62,000	58%	84,000
3 TeV machine	50.7	5.6	0.4	4.8	0	0	250,000	106,000	58%	144,000

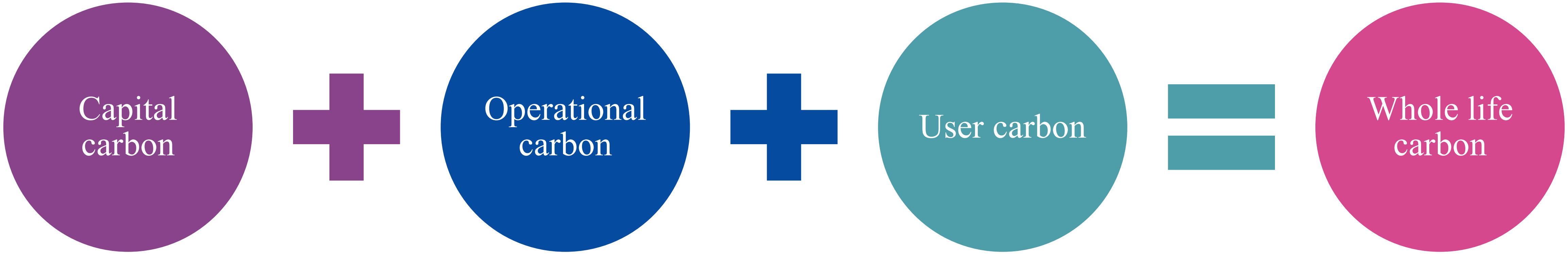
tunnel			shaft no	depth (m)
3 TeV	1.5 TeV	380 GeV	1	135
			2	135
			3	112
			4	125
			5	72
			6	108
			7	125
			8	88
			9	110
			10	147
			11	180

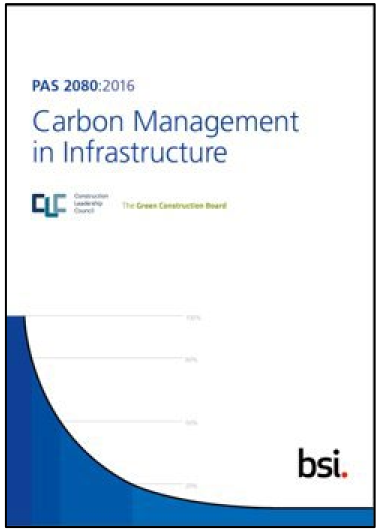
References:
- Project Implementation Plan 20 Dec 2018
- Conceptual Design Report 10 Oct 2012

ARUP

PAS 2080

Carbon Management in Infrastructure





PAS 2080: 2016 Carbon management in infrastructure.

ARUP

Components of WLC

In engineering Infrastructure these classifications of GHG emissions are more commonly used:

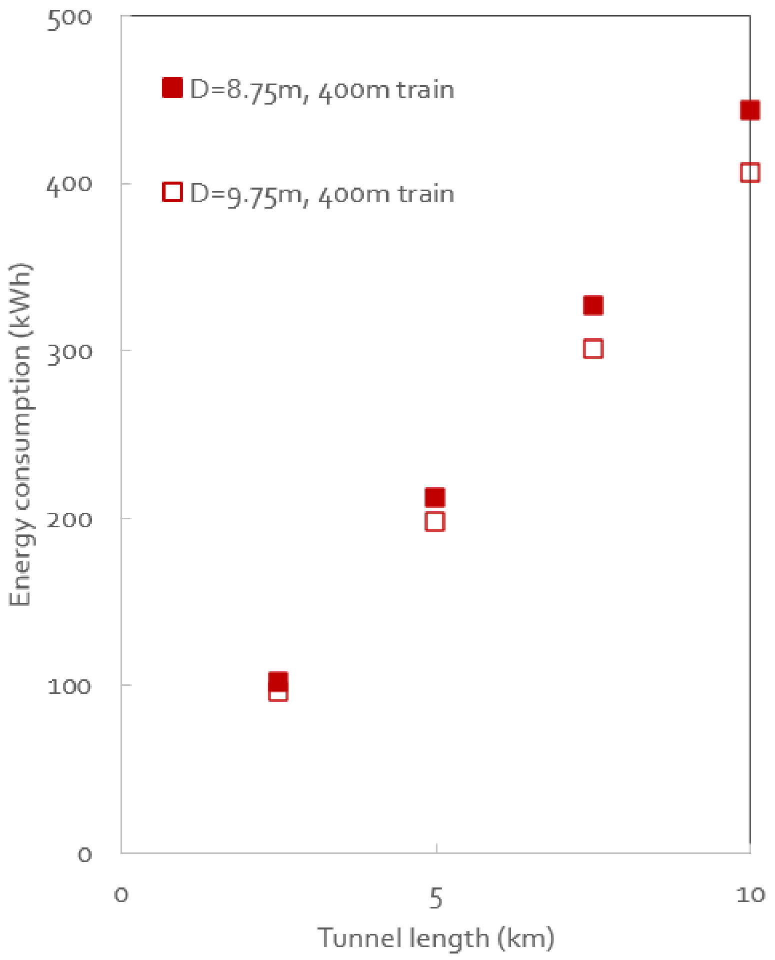
- **Capital carbon**, or ‘**CapCarb**’, refers to emissions associated with the creation of an asset. Capital carbon is being adopted within the infrastructure sector because it accords with the concept of capital cost. (the term “embodied carbon” will continue to be used at a product-level, whereas capital carbon will have greater relevance at an asset-level).
- **Operational carbon**, or ‘**OpCarb**’, describes emissions associated with the operation and maintenance of an asset. It is analogous to operational cost and is quantified in tCO2e/year.
- **End-user carbon**, or ‘**UseCarb**’ describes emissions from the end-users of infrastructure assets. Although not directly controlled by infrastructure asset owners, UseCarb can be influenced.
- **Whole life carbon**, combines the three and is analogous to whole life cost.

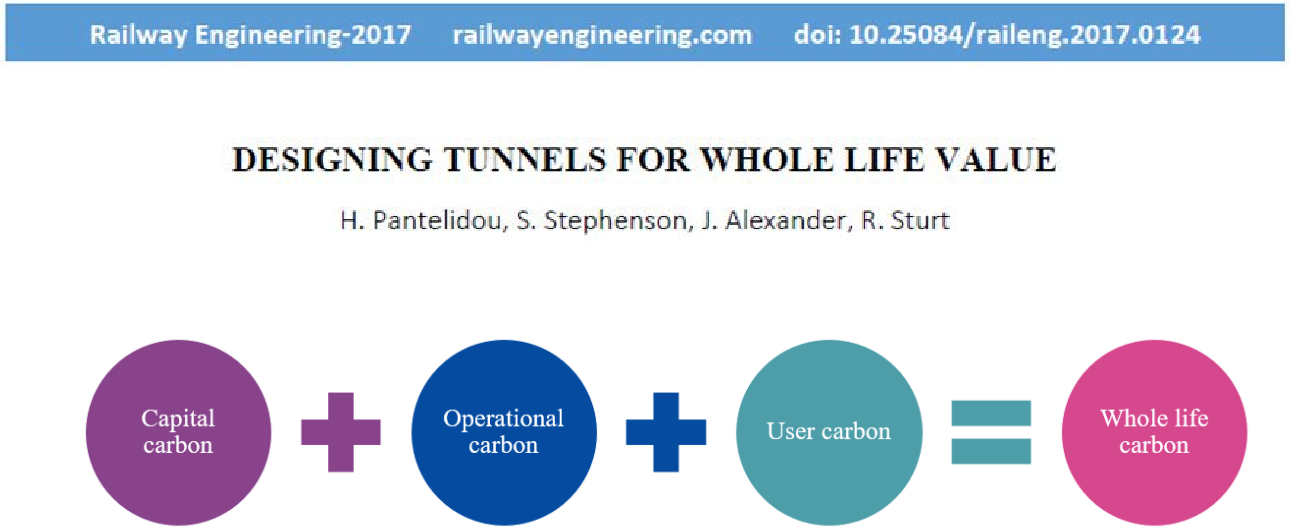
HM Treasury

Infrastructure Carbon Review

ARUP

Capital carbon investment for operational savings

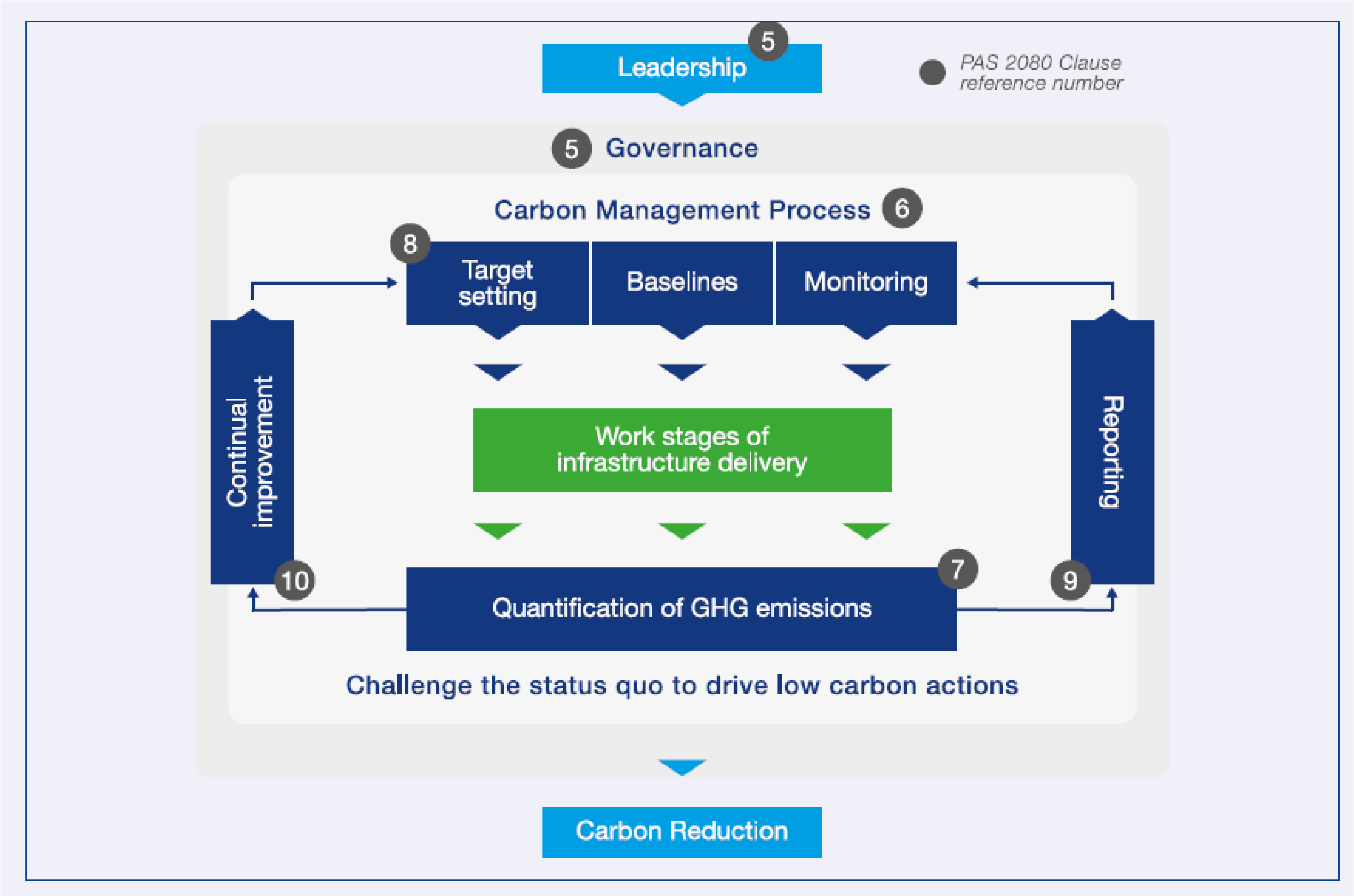




Components of Carbon management

ARUP

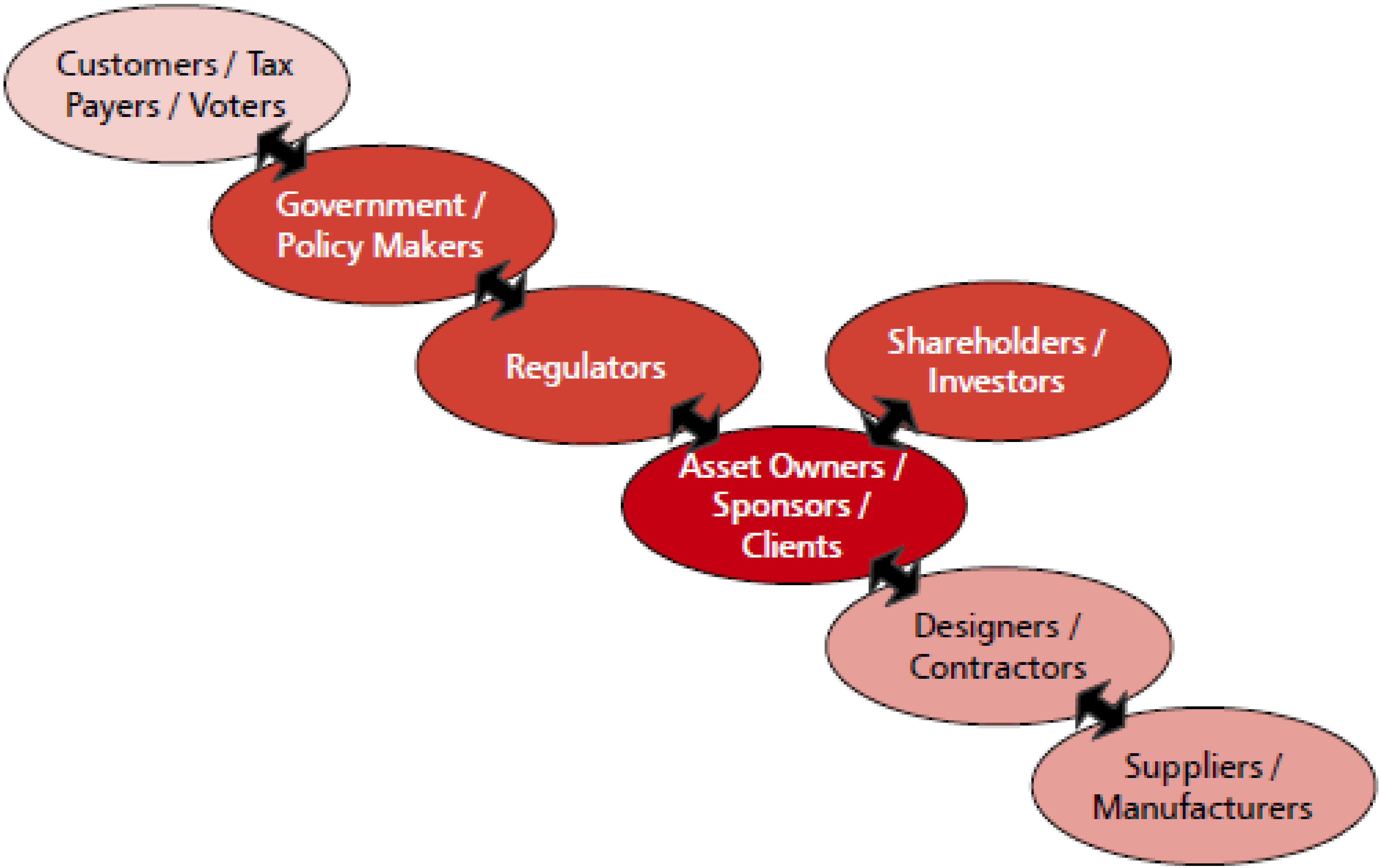
1. Quantification of whole life GHG emissions
2. Target setting, baseline setting and monitoring
3. Reporting
4. Continual improvement



PAS 2080: 2016 Carbon management in infrastructure. Available at https://shop.bsigroup.com/products/carbon-management-in-infrastructure?_ga=2.165334716.2047882221.1633446853-1508464572.1605203277

Value chain involved

ARUP



HM Treasury

Infrastructure Carbon Review

ARUP

The carbon reduction hierarchy

From PAS 2080

Build nothing

Build less

Build clever

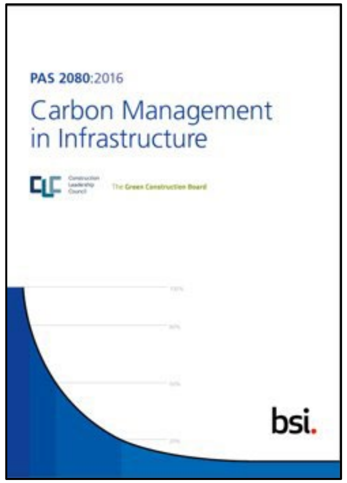
Build efficiently

Saves £££

Saves ££

Saves / costs £

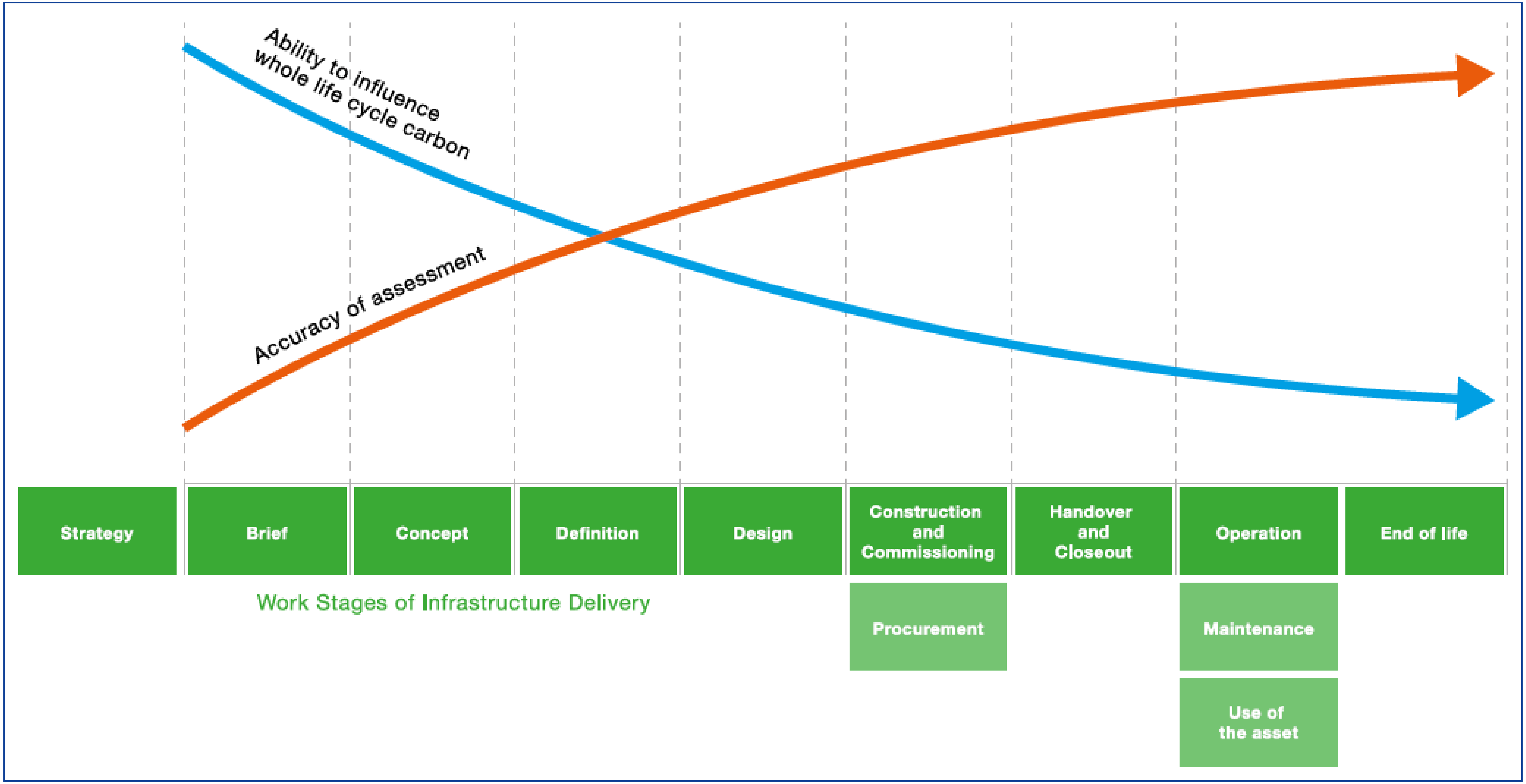
May need investment £



Accuracy vs Influence

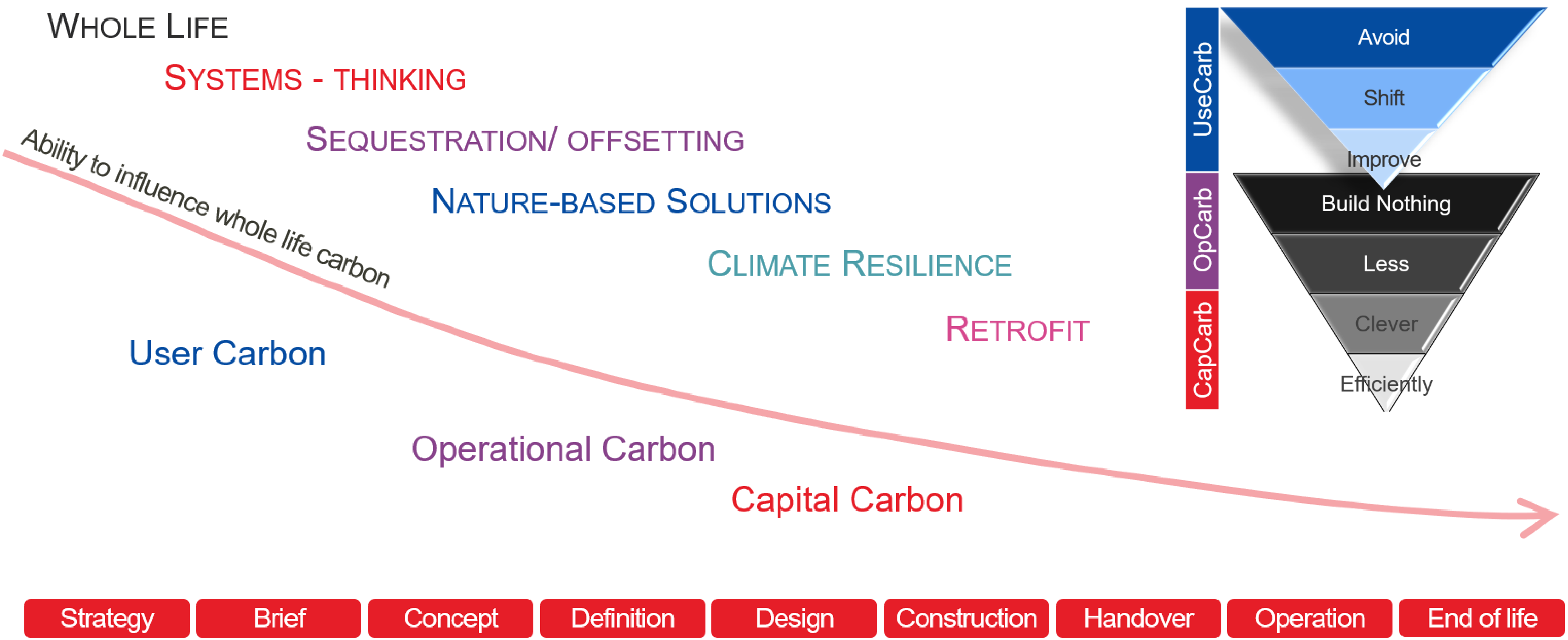
ARUP

Ability to influence carbon reduction across the different work stages of infrastructure delivery



PAS 2080: 2016 Carbon management in infrastructure. Available at https://shop.bsigroup.com/products/carbon-management-in-infrastructure?_ga=2.165334716.2047882221.1633446853-1508464572.1605203277

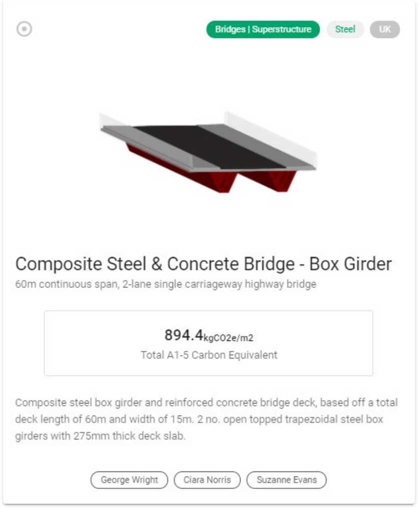
ARUP



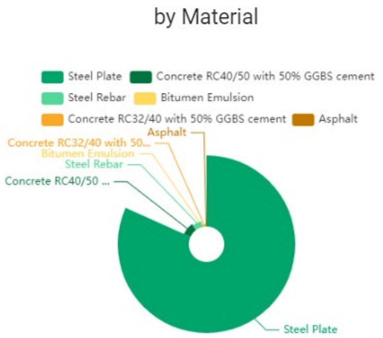
WHOLE LIFE
SYSTEMS - THINKING
SEQUESTRATION/ OFFSETTING
NATURE-BASED SOLUTIONS
CLIMATE RESILIENCE
RETROFIT
Ability to influence whole life carbon
User Carbon
Operational Carbon
Capital Carbon
UseCarb
OpCarb
CapCarb
Avoid
Shift
Improve
Build Nothing
Less
Clever
Efficiently
Strategy
Brief
Concept
Definition
Design
Construction
Handover
Operation
End of life

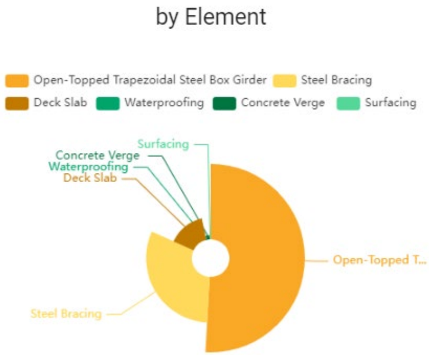
ARUP

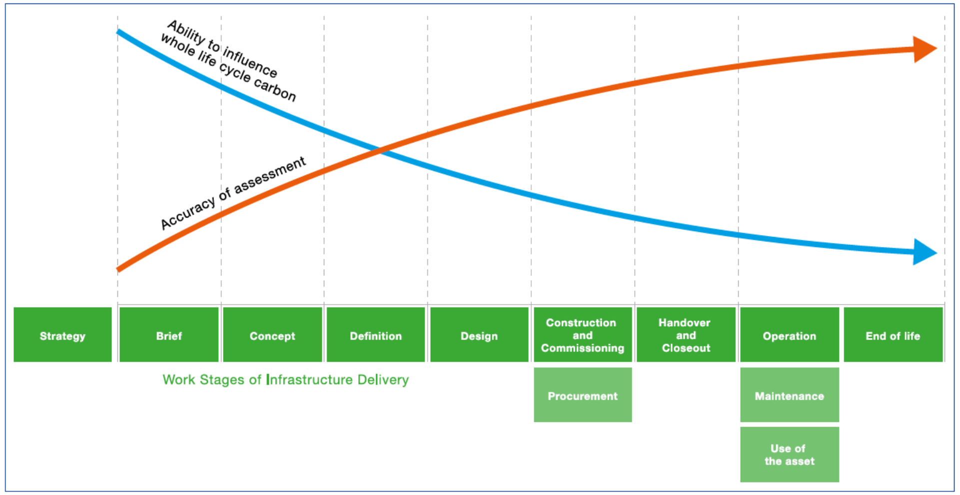
Comparing options and estimating carbon



- Qualitative eg for most "build nothing" options
- Libraries of typical elements
- "Back of envelope" volumes x carbon factors
- BIM interfaces
- Commercial tools eg One Click LCA, eTc

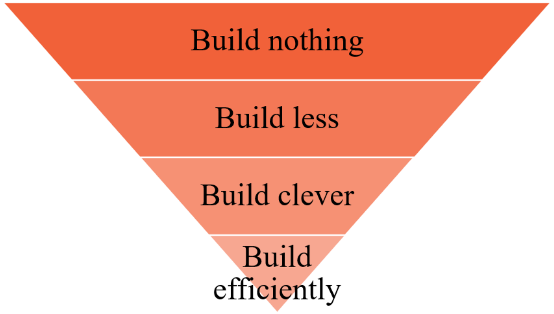




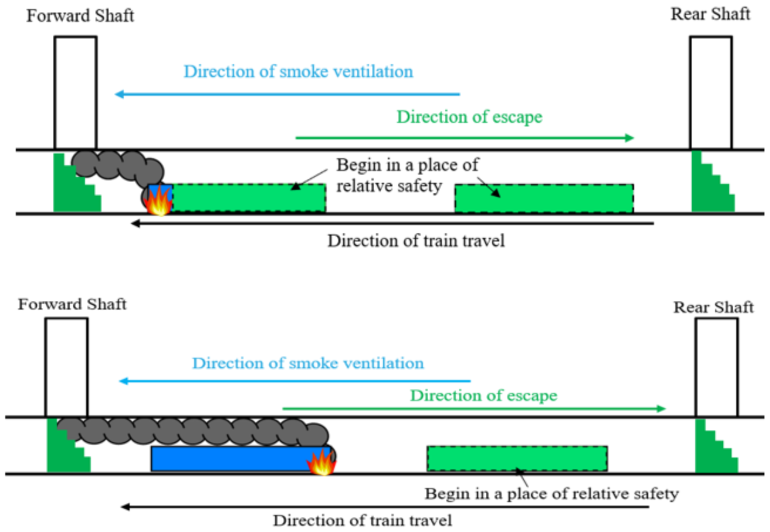


Build nothing

Deleting shafts on a tunnelled rail project



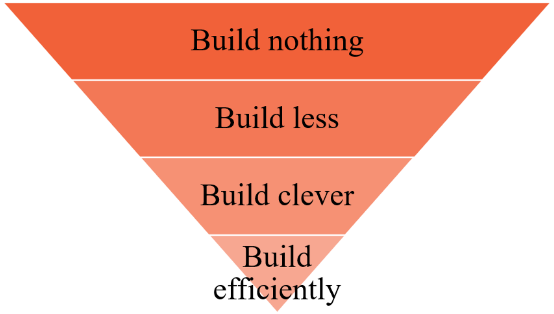
- Combination of
  - Fire Engineering
  - Risk and Resilience
  - Geotechnical
  - Rail Systems
  - Tunnelling



to remove the need for eight ventilation and intervention shafts from over 21km of rail running tunnel

Build less (= “good design”?)

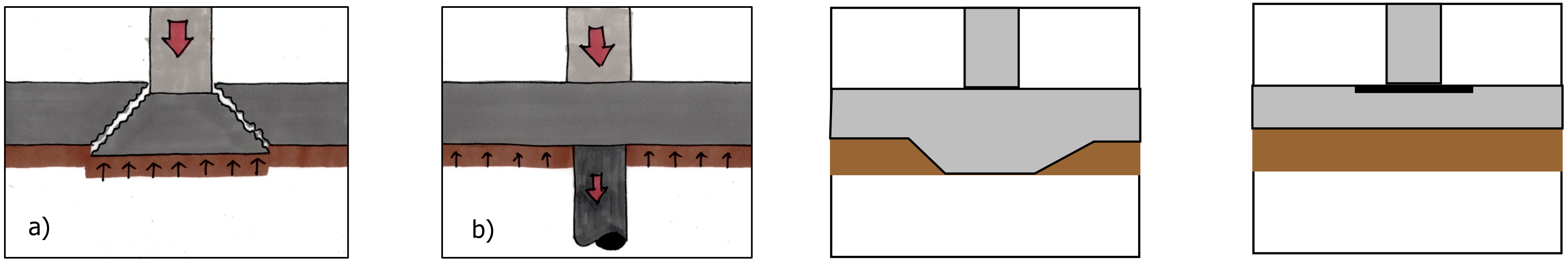
Reducing base slab thickness



Underground rail station with large oversite development loads.

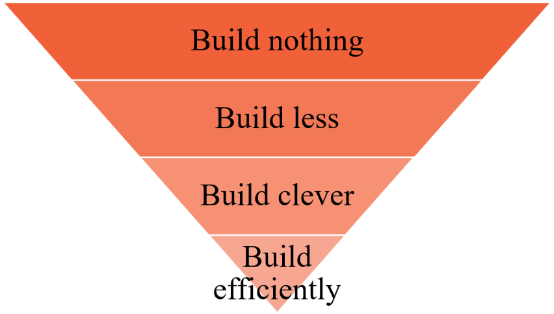
Column spacing dictated by platforms.

- Large column loads → high punching shear → thick base slab
- ~20% of the station’s capital carbon



Build clever

Lower carbon concrete mixes (but GGBS is a finite resource)



Property	Alternative material (see footnote for key)										
	GGBS	FA									
Embodied carbon	↓	↓	↓	~↓	↓	~↓	↓ / ~↓	↓	~↓	↓ / ~↓	↓ / ~↓	~ ~↓
Fresh properties	~↑	~↑	~↓	~↓	~↓	~↓	U	↑* / ↓**	~↓	→	U	~↓
Strength (early)	~↓	~↓	~↑	~↑	~↓	~↓	~↓	~↓	U	U	~↓	~↑
Strength (long-term)	~↑	~↑	~↑	~↑	~↑	~↑	~↑	~↓	→	→	→	~↑
E-modulus	→	→	→	→	U	U	U	→	U	~↓	U	U
Shrinkage	~↑/→	~↑/→	↑	~↓/→	U	U	U	~↓	U	~↑	U	~↑
Creep	~↑/→	~↑/→	~↓	~↓/→	U	U	U	U	U	~↑	U	U
Durability (Chlorides)	↑	↑	↑	~↑	~↑	~↑	~↑	~↑	~↑	~↑	U	→
Durability	↑* / ↓**	↑* / ↓**	~↑/→	~↓	U	U	U	~↓	~↑	~↑	U	U

Property	Alternative material (see footnote for key)										
	GGBS	FA									
(Carbonation)												
Durability (ASR, DEF.)	↑	↑	↑	↑	↑	↑	~↑	↑	~↑	U	U	U
Standardisation	G	G	G	M	M	M	L	L	L	L	L	L
Availability	M	M	M	M	G	M	L	G	L	L	L	L
Cost	→	→	~↑	~↑	~↓	~↑	~↑	↓	→	~↑	U	~↑

(# Different technologies would have different properties. Indicative effects only).

Notation:

"→" as Portland cement; "↑" greater than Portland cement; "↓" less than Portland cement,

"~" before the arrows indicates "somewhat".

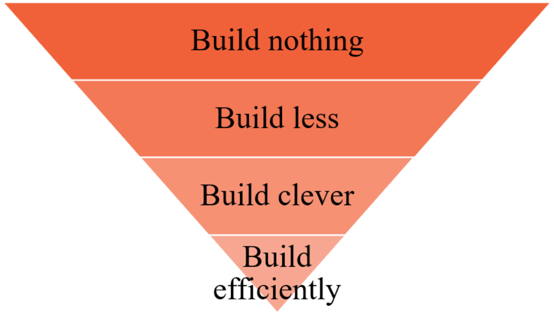
The colour scale represents where 'greater than' and 'less than' are beneficial/detrimental within typical applications, green being beneficial and red being detrimental.

"G", "M", "L" and "U" are used for good, moderate, low and unknown, respectively.

Also:

- Ground improvement

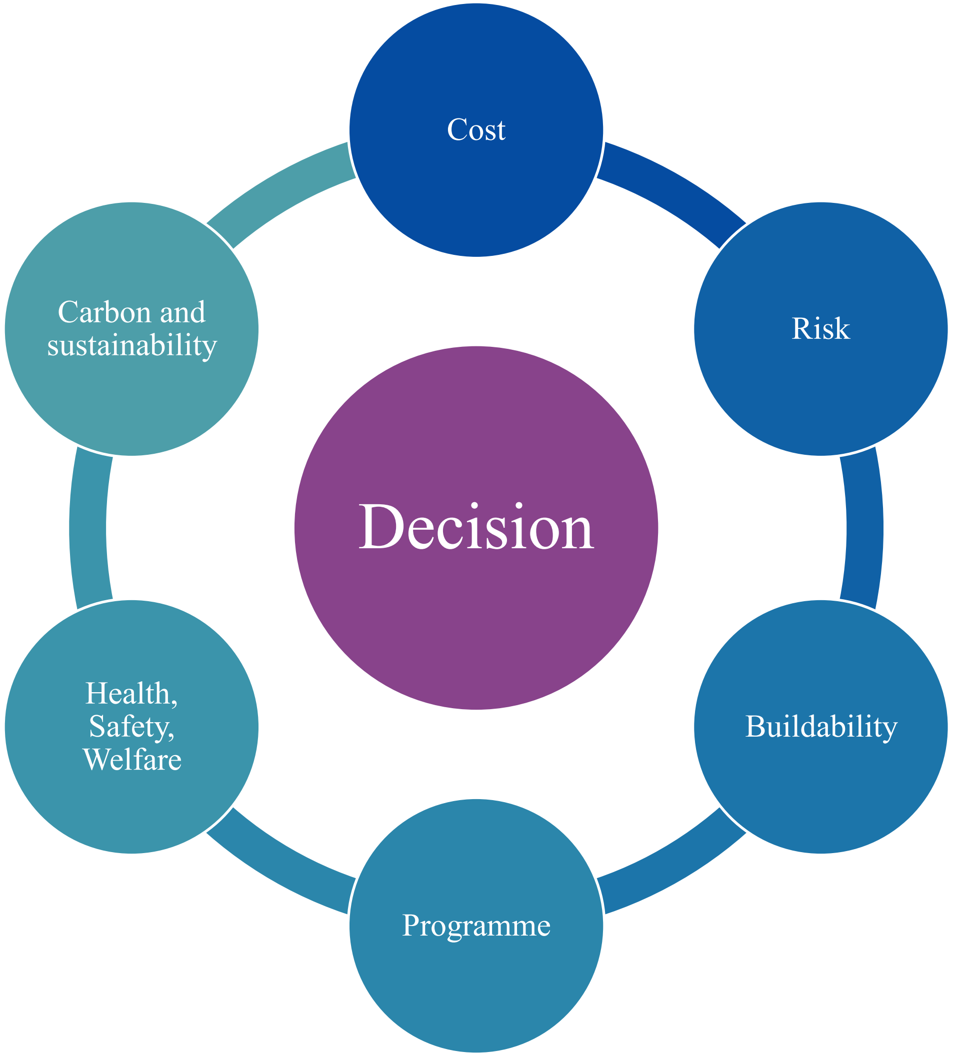
Build efficiently



- Prefabrication?
- Connect site to the grid
- Electric plant
- Cut and fill balance
- Local sourcing

Including carbon in decision-making

The power of the estimate



ARUP

Carbon Management in Infrastructure

Arup capabilities

Level of input	Product / deliverable
Whole life Carbon measurement of the design as is	Carbon baseline
Awareness / attendance at progress and design coordination meetings with the aim of influencing the design / construction methods;	Carbon management opportunities report
Full collaboration between all parties in accordance with PAS2080 to drive carbon down to the greatest degree and create an exemplar project for CERN aligning with carbon reduction targets and plans of the wider jurisdiction and UN accord at COP 21 (Paris) and 26 (Glasgow)	Carbon management plan, regular carbon update reports tracking progress and target achieved, opportunities register and realisation process and reports

ARUP

Q & A

- Cost benefit?
- SCL?
- Delivery?

ARUP

Contact