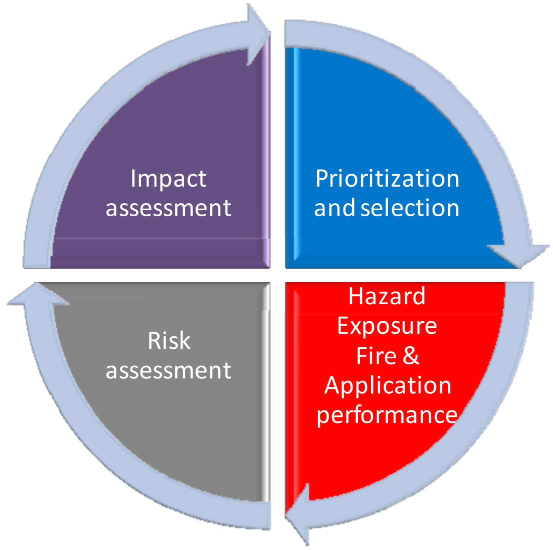

Figure 1: ENFIRO chemical alternative cycle.

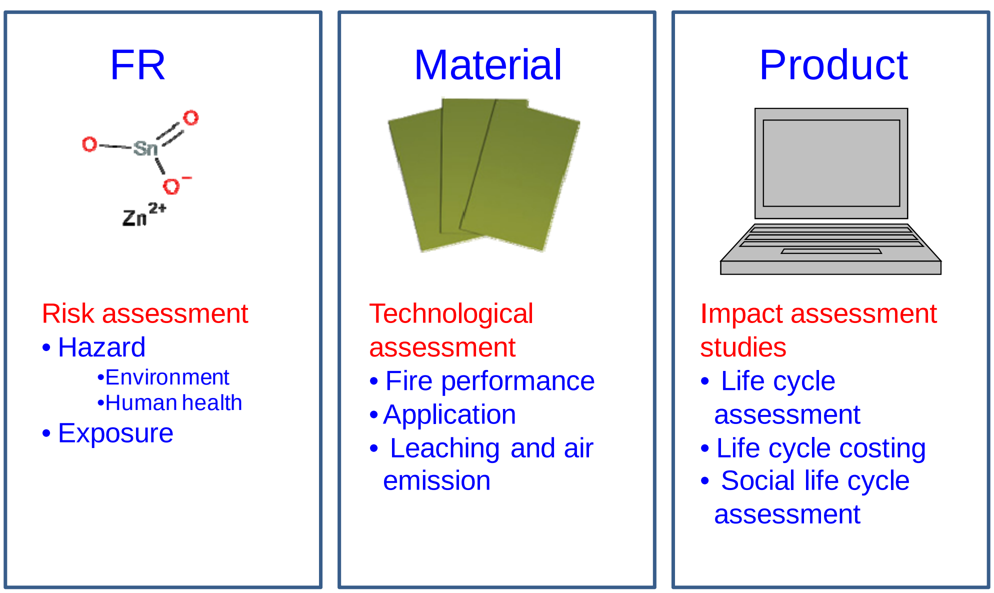

Figure 2: ENFIRO's three levels of comparative assessment.

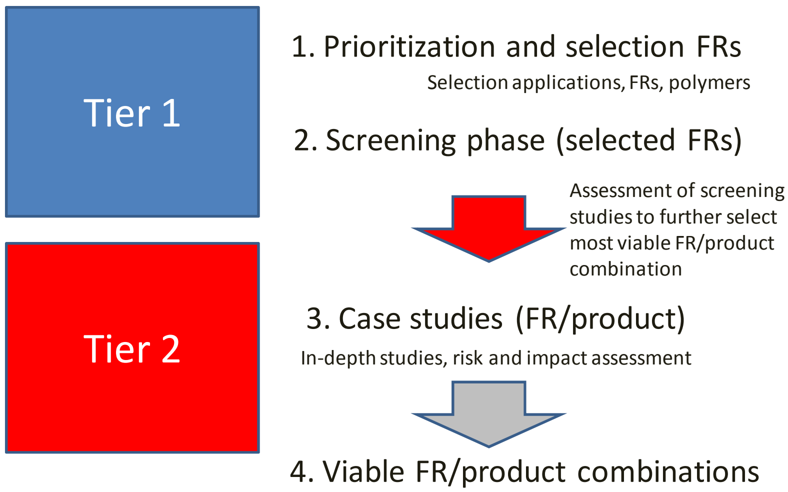

Figure 3: ENFIRO tiered approach of screening and case studies.

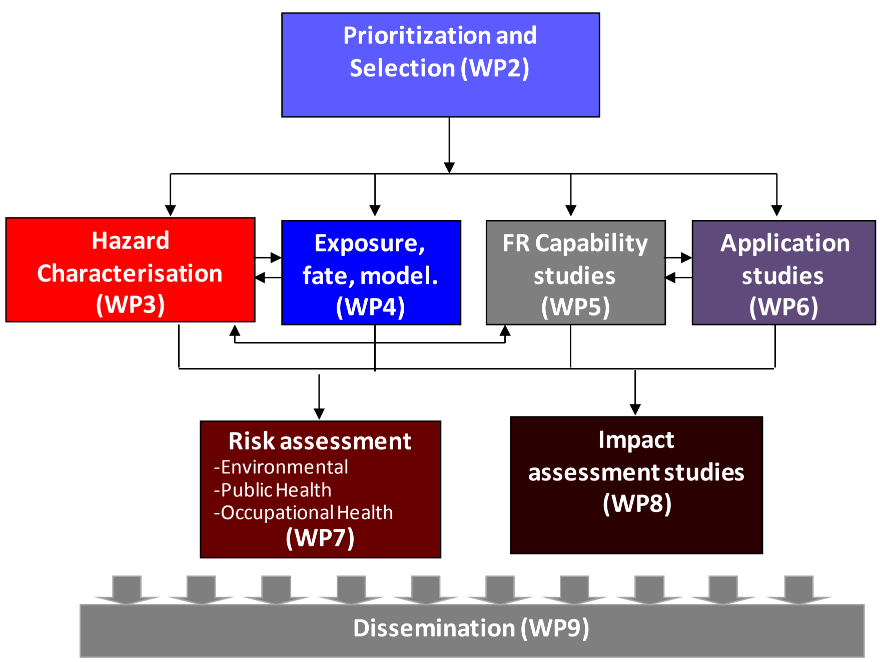

Figure 4: Overview of the structure of the project.

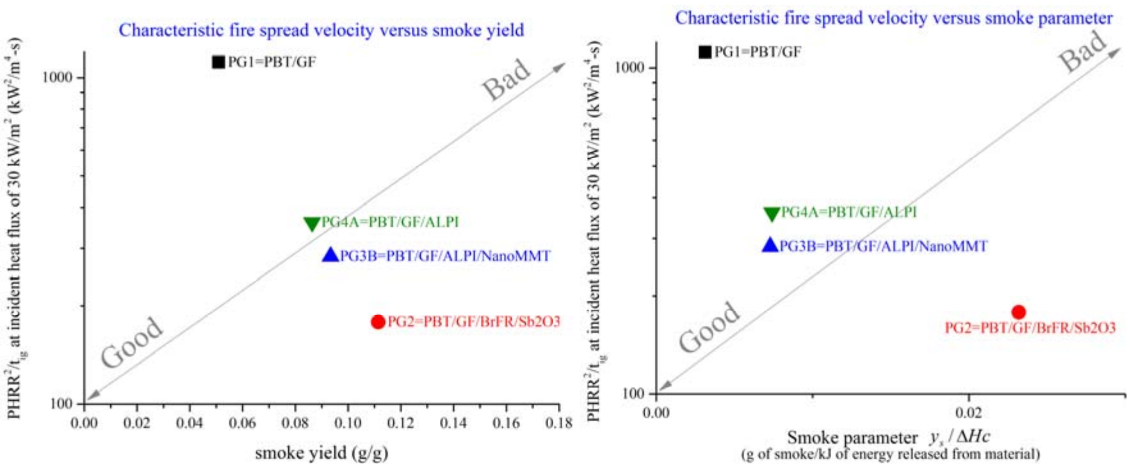

Figure 5: Characterisation of both the UL94 and the large scale fire behaviour of PBT formulations using two parameters for fire growth and smoke production deduced from cone calorimeter experiments. Characteristic fire spread velocity versus smoke yield (left) and smoke parameter (right).

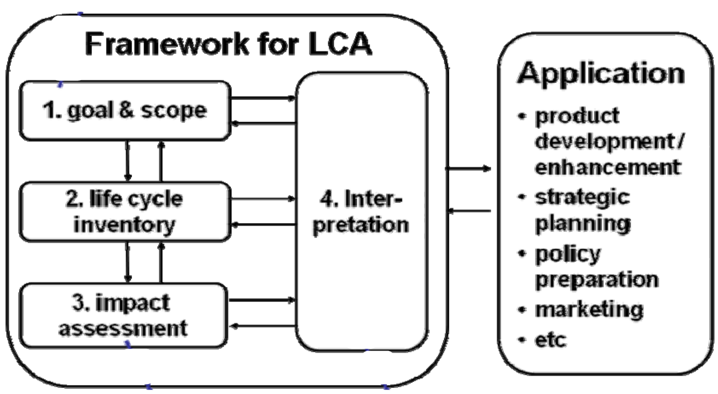

Figure 6. General framework of an LCA study, with the specific deliverables for the Env-LCA in the ENFIRO study indicated.

Table 1: List of selected commercially viable alternative FRs in combination with polymers that were studied in ENFIRO. List includes feedback from the ESF.

Polymer materials	**Mainly used BFR**	**Applications**	**HFFR selected**
Epoxy resins	TBBPA	Printed circuit boards, Electronic components encapsulations, Technical laminates	9,10-Dihydro-9-oxa-10-phosphosphaphenantrene oxide (DOPO), Aluminium hydroxide (ATH), Fyrol PMP
Epoxy encapsulates	DecaBDE	Electrical *Encapsulating* & Casting	Melamine polyphosphate (MPP), Boehmite, Aluminium diethylphosphinate (Alpi), ATH, Zinc hydroxyl stannate (ZHS), Zinc stannate (ZS), Zinc borate (ZB)
HIPS/PPE	DecaBDE/ATO	Housings for business machines, dashboards, toys, equipments for refrigerator, telephones, and other consumer electronics	Resorcinol bis (biphenyl phosphate) (RDP), Bis phenol A bis (biphenyl phosphate) (BDP), Triphenylphosphate (TPP)
PC/ABS	DecaBDE/ATO	Housings for business machines, dashboards, toys, equipments for refrigerator, telephones, and other consumer electronics	RDP, BDP, TPP
Polyamide 6 Polyamide 6,6	Brominated polystyrene (BPS)/ATO	Electrical & electronic equipment, connectors, switches etc.; encapsulated electronic components	Alpi, MPP , ZB, ZS, Melamine cyanuarate (MC)
Polybutylene therephthalate (PBT)	Brominated polystyrenes/ATO	Electrical & electronic equipment, connectors, switches etc.; encapsulated electronic components	Alpi, Nanoclay (organo-clays based on montmorillonite, nano-MMT)
Ethylene vinyl acetate (EVA)	DecaBDE / ATO	Wire & Cable	ATH, Magnesium hydroxide $(Mg(OH)_2$. ATH coated with Zinc hydroxy stannate (ZHS), Boehmite
Textile coatings	DecaBDE/ATO	Protective clothing, Carpets, curtains, upholstered fabrics, tents, interior in public transportation	Ammonium polyphosphate (APP), Pentaerythritol (PER), MPP, ZB
Intumescent coating: High impact	DecaBDE/ATO	Housings of electronic products	Novel application to attempt to reach V(0) for pure HIPS with intumescent coating based on APP, PER, MPP

polystyrene (HIPS)			

Table 2: Summary information on the hazard characterization of the selected HFFRs.

Less of concern	Ammonium polyphosphate (APP) Aluminium diethylphosphinate (Alpi) Aluminium hydroxide (ATH) Melamine polyphosphate (MPP) 9,10Dihydro-9-oxa-10-phosphaphenanthrene (DOPO) Zinc stannate (ZS) Zinc hydroxystannate (ZHS)	• Inorganic and organic substances with low acute (eco-)toxicity and no bioaccumulation potential • Chemical stability required for application results in limited degradation (persistence) • Alpi showed moderate chronic aquatic toxicity • Stannates: there is no immediate concern due to poor bioavailability. Some (neuro-)tox effects were detected during initial screening studies (in-vitro cell), but no (neuro-)tox effects were measured in preliminary animal studies (in-vitro mice).
Some concern for potential impact on environment and humans	Resorcinol bis(diphenylphosphate) (RDP) Bisphenol-A bis(diphenylphosphate) (BDP)	• RDP toxicity to aquatic organisms is main concern, may be linked to by-products (TPP). Low and high toxicity are found for same test species, which may be due to batch differences in the amount of TPP present as by-product. • BDP is persistent
Of concern, risk assessment necessary	Triphenyl phosphate (TPP) Nanoclay (Cloisite)	• TPP very toxic to aquatic organisms is main concern, potential endocrine effects • Nanoclay showed strong in vitro neurotoxicity. May be due to the nanoparticle coating, additional studies needed. Information on the leaching behaviour of nanoclays from polymers is also needed.

Table 3: Most viable HFFR/polymer combinations from a fire performance, application and hazard viewpoint.

Polymer materials	**HFFR selected**
Epoxy resins	DOPO, ATH
Epoxy encapsulates	MPP, Alpi, ATH, ZHS, ZS
HIPS/PPE	RDP, BDP. Some hazard concern less desirable FRs.
PC/ABS	RDP, BDP. Some hazard concern less desirable FRs.
Polyamide 6 Polyamide 6,6	Alpi, MPP, ZS
Polybutylene therephthalate (PBT)	Alpi
Ethylene vinyl acetate (EVA)	ATH, ATH coated with ZHS
Textile coatings	APP, PER, MPP
HIPS: Intumescent coating:	Mixture of APP, PER, MPP. Novel application to attempt to reach V(0) for pure HIPS with intumescent coating

ENFIRO list of beneficiaries

Partner	Country	Contact person
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IRIS Vernici s.r.l.	Italy	Claudio Pagella
Procoat	Italy	Giancarlo Baldi
IVAM	Netherlands	Hildo Krop
Stockholm University	Sweden	Cynthia de Wit
IRAS, Utrecht	Netherlands	Remco Westerink
Swerea IVF AB	Sweden	Dag Andersson
University of Amsterdam	Netherlands	John Parsons
Callisto	United Kingdom	Tom McInnes
ITRI Innovation Ltd.	United Kingdom	Paul Cusack