Resource recovery from wastewater with bioelectrochemical systems

METEOR

Microbial Electrochemical TEchnology fOr Resource Recovery

Ian M. Head

NERC Resource Recovery from Waste

NERC SCIENCE OF THE ENVIRONMENT

Newcastle University

Resource recovery from wastewater with bioelectrochemical systems

http://www.meteorr.ac.uk/

Project overview

- Project teams
  - Newcastle

Ed Milner, Henriette Christiansen, Alison Vipond, Beate Christgen, Martin Spurr, Ana Suarez-Suarez

Ian Head, Eileen Yu, Keith Scott, Tom Curtis

  - Manchester

Rick Kimber

Jon Lloyd, Vicky Coker

  - South Wales

Hitesh Boghani

Iano Premier, Alan Guwy, Richard Dinsdale

  - Surrey

Kok Siew Ng

Jhuma Sudhukhan

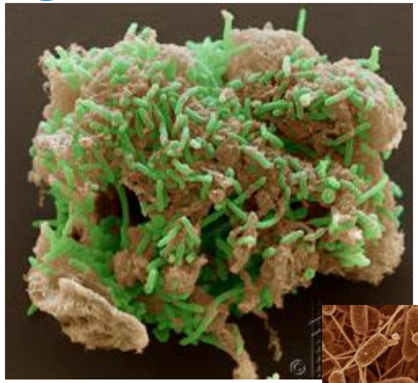
NERC SCIENCE OF THE ENVIRONMENT

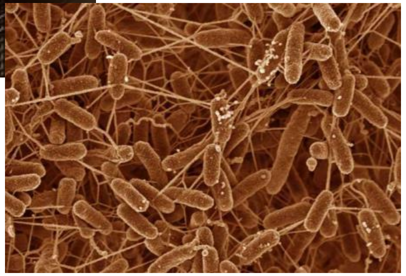
BES rely on fundamental principles from global biogeochemical cycles

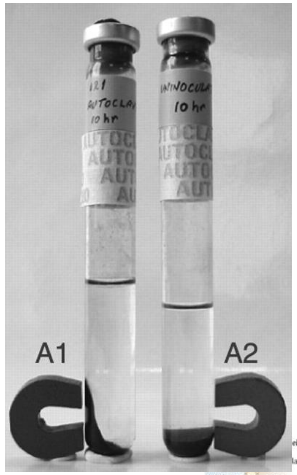
Metal oxide reduction can account for 30-90% of organic carbon turnover in marine sediments and may be highly significant for organic carbon mineralization in low sulfate environments (Canfield et al., 1993. Marine Geology, 113, 27–40)

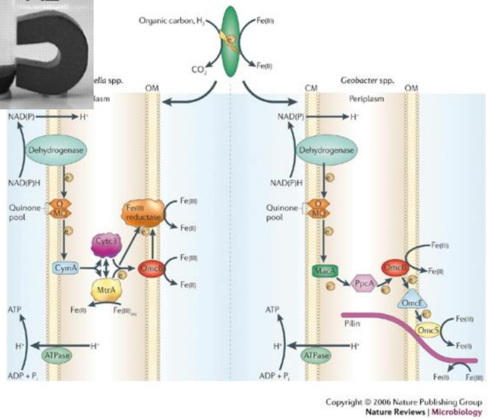
The mechanisms that have evolved to allow bacteria to transfer electrons to solid phase electron acceptors are exploited in microbial bioelectrochemical systems with electrodes as e^- acceptors/donors

www.geobacter.org

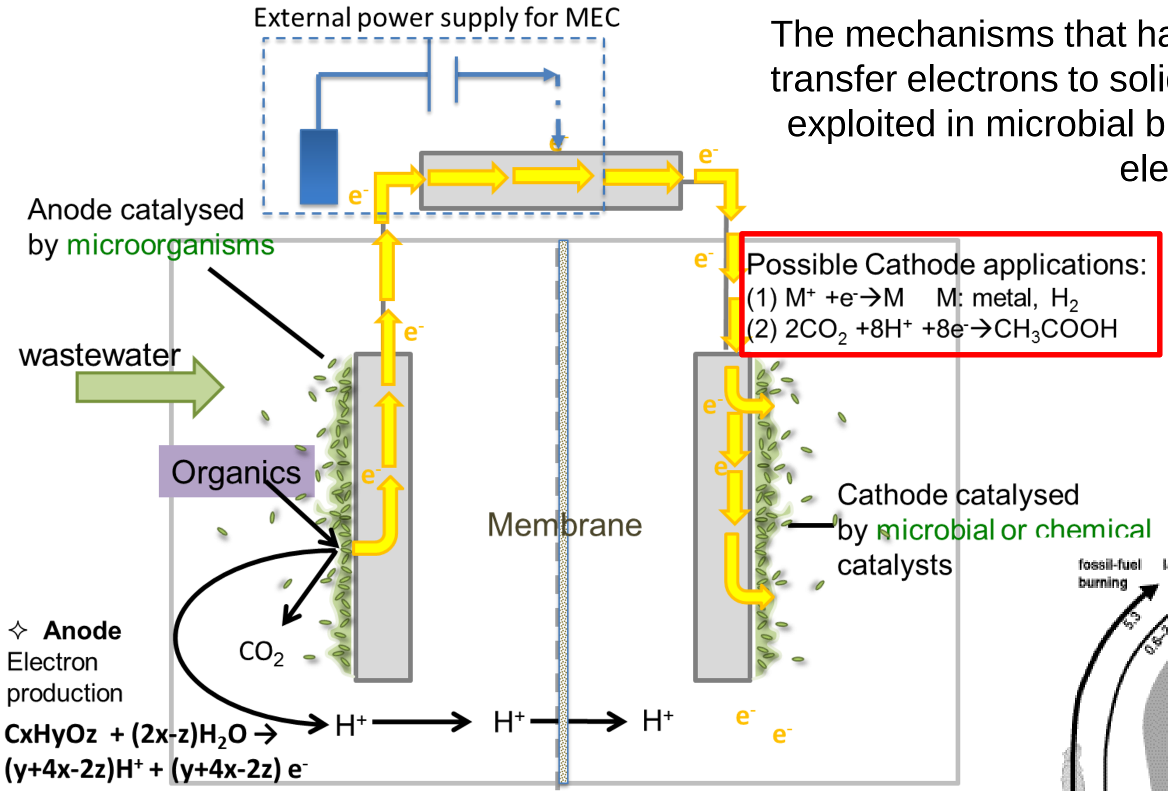


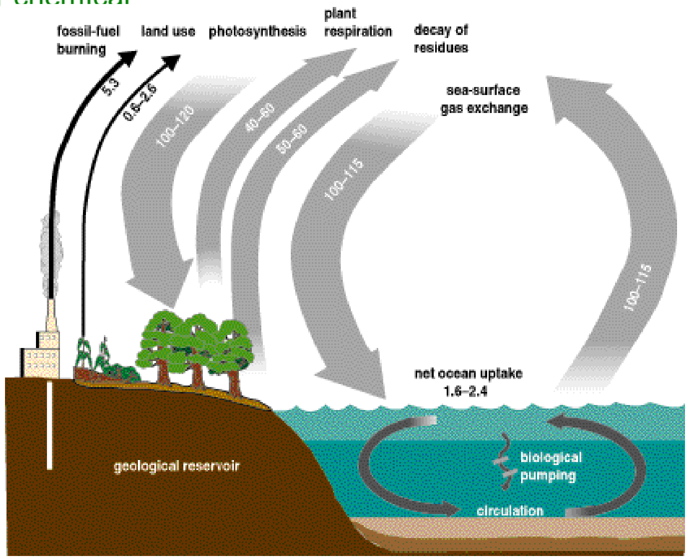






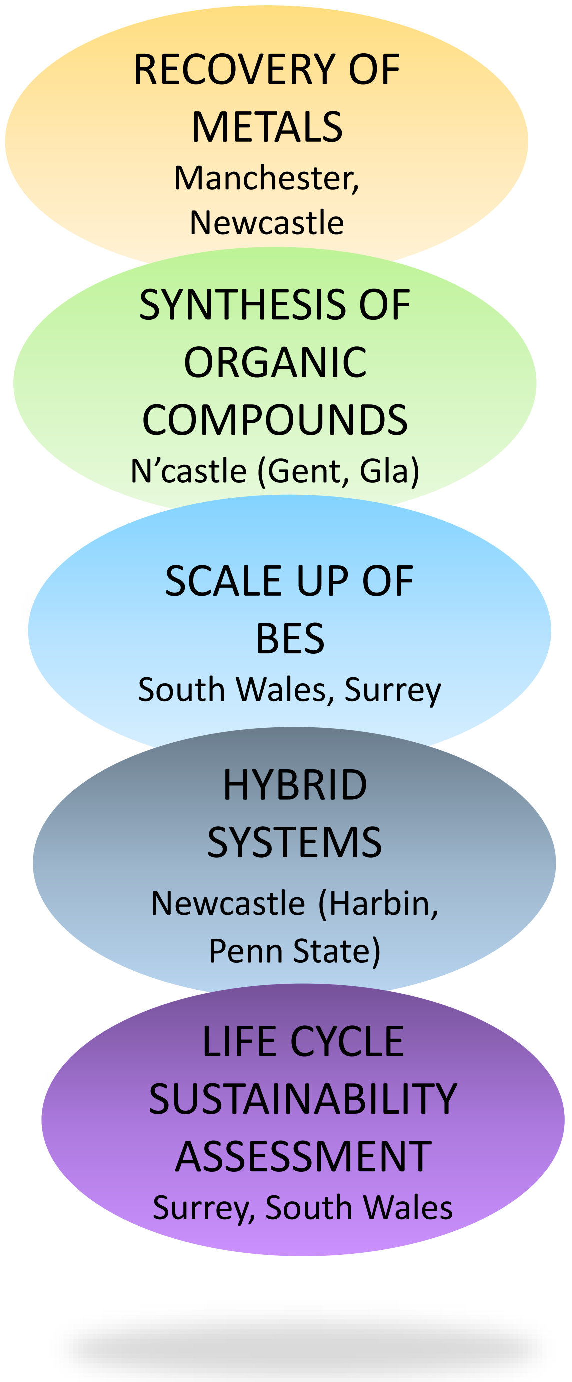
Weber, K.A. et al. (2006). Nature Reviews Microbiology 4, 752-764





Project overview

- Development of BES for RRfW
  - Wastewater-driven microbial bioelectrochemical system
  - Reducing power harvested from wastewater to drive cathodic reactions
  - Selective metal reduction/recovery
  - Organic compound synthesis
  - Integration with other process
- Life cycle sustainability assessment of resource recovery vs electricity recovery and competing resource recovery processes
- Modelling
- Scale-up

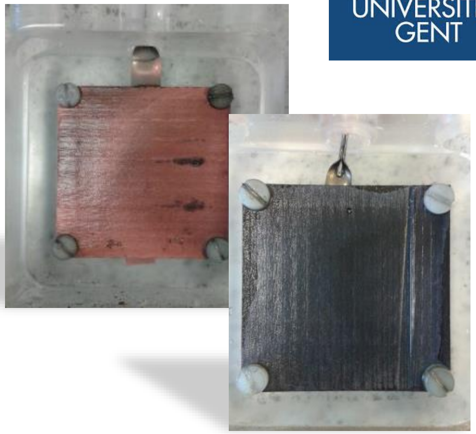


Progress

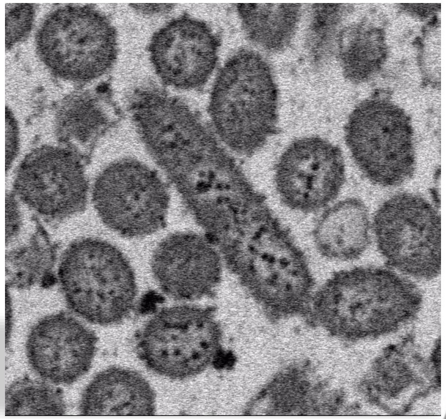
UNIVERSITEIT GENT

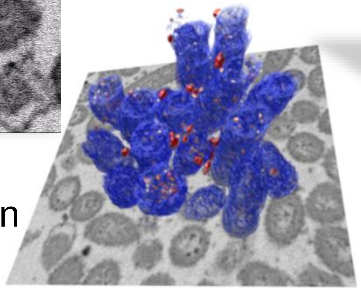
Newcastle University

Chivas Brothers
Pernod Ricard



MANCHESTER 1824





3View - Serial Block Face Scanning Electron Microscopy

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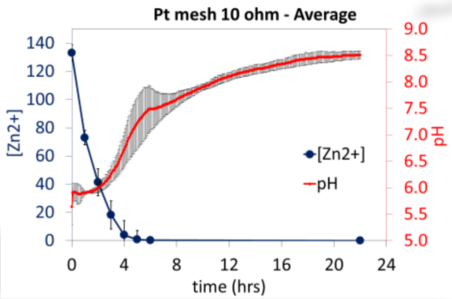
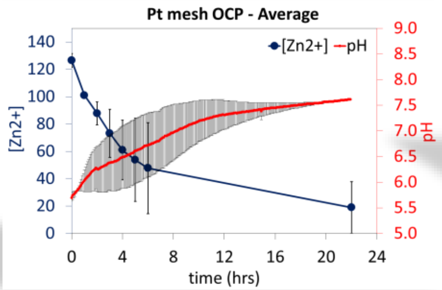
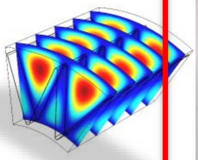
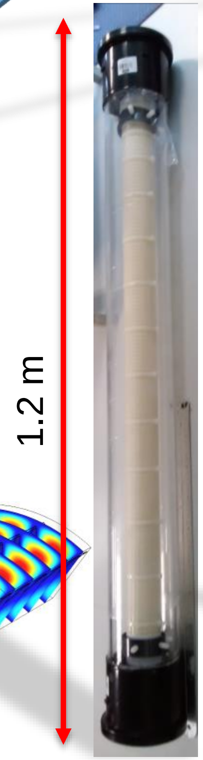
TATA
TATA STEEL







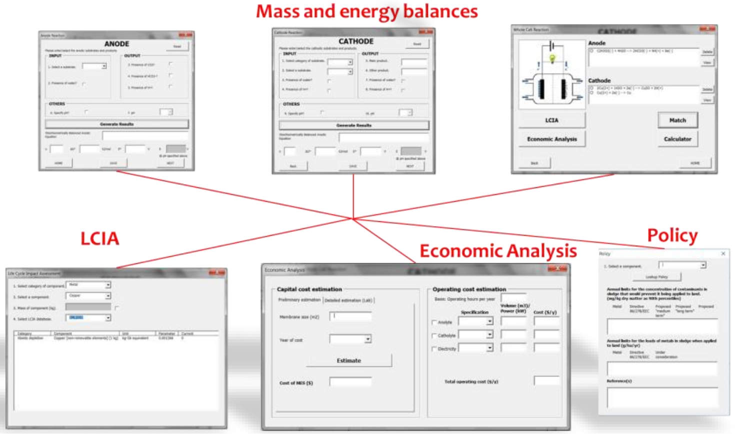


University of South Wales
Prifysgol De Cymru

RECOVERY OF METALS
Manchester, Newcastle

SCALE UP OF BES
South Wales, Surrey

LIFE CYCLE SUSTAINABILITY ASSESSMENT
Surrey, South Wales



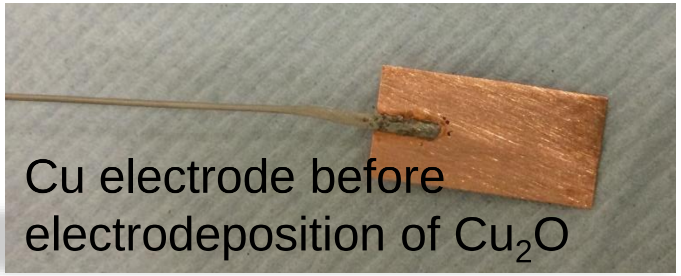
UNIVERSITY OF SURREY

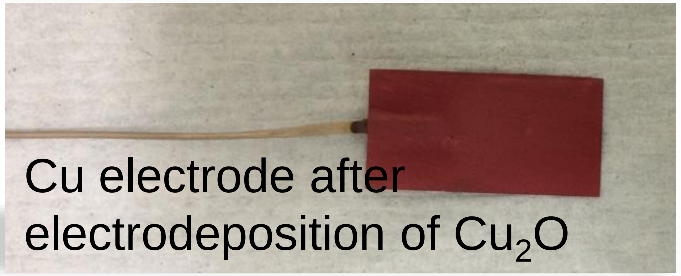
Progress

- Catalysts for cathodic electrochemical CO_2 reduction
  - Cu_2O electrodes for methanol synthesis
  - Sn and SnO/SnO_2 catalysts for formate synthesis
  - poly-Co-tetraaminophthalocyanine for formate synthesis
- Microbial electrosynthesis by cathodic CO_2 reduction

SYNTHESIS OF ORGANIC COMPOUNDS
N'castle (Gent, Gla)

Paniz Izadi
PhD Student


Cu electrode before electrodeposition of Cu_2O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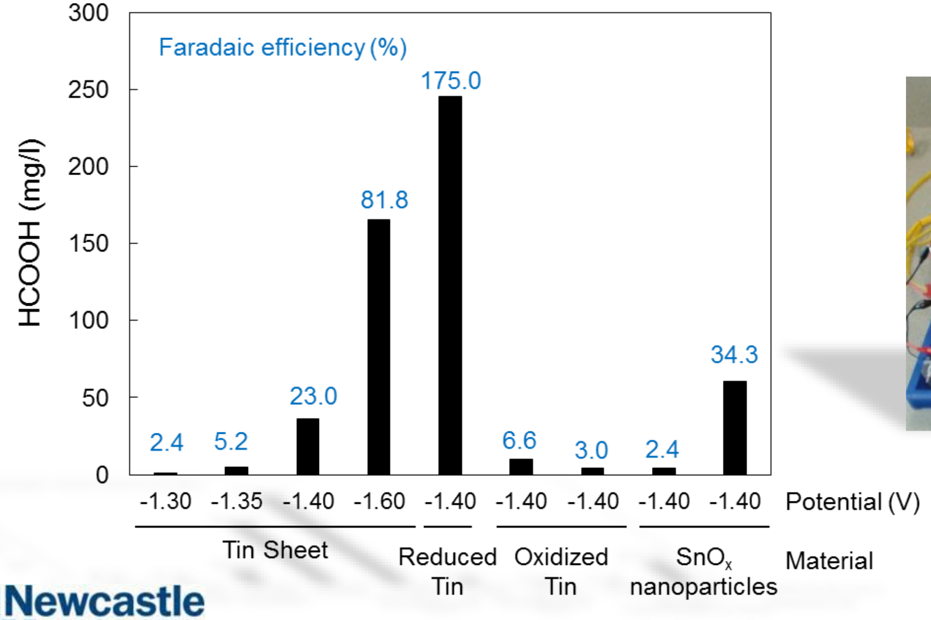

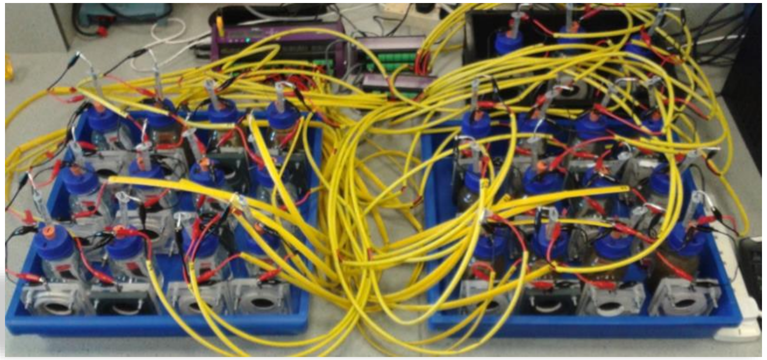

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Newcastle University

Cu from wastewater using BES

- Metal removal from aqueous wastestreams is useful
- Recovery of valuable metals would be better still

Chalcocite (Cu_2S), Cu ore

Cu recovery from wastewater using BES

Elshkaki, A., Graedel, T., Ciacci, L. & Reck, B. (2016). Copper demand, supply, and associated energy use to 2050. Global Environmental Change, 39: 305–315. DOI: 10.1016/j.gloenvcha.2016.06.006.

- Global demand for copper projected to increase by 213% to 341% by 2050
- This could result in 2.4% of global energy demand being directed towards Cu recovery
- Copper reserves could be depleted in 20 to 60 years
- New and better ways to recycle and recover Cu are needed

Chuquicamata open pit copper mine, Chile.

Elshkaki, A., Graedel, T., Ciacci, L. & Reck, B. (2016). Copper demand, supply, and associated energy use to 2050. Global Environmental Change, 39: 305–315. DOI: 10.1016/j.gloenvcha.2016.06.006.

Cu recovery from wastewater using BES

- Can BES systems be developed for recovery of copper from copper containing wastestreams?

Chuquicamata open pit copper mine, Chile.

Stakeholder engagement developing methods for recovery of copper from a distillery wastestream

Chivas Brothers
Pernod Ricard

The Scotch Whisky Industry

Annual exports of
£4 bn

10,800 Scottish Jobs
>7,000 in Rural Communities
40,000 in UK

Direct exports to
175 countries

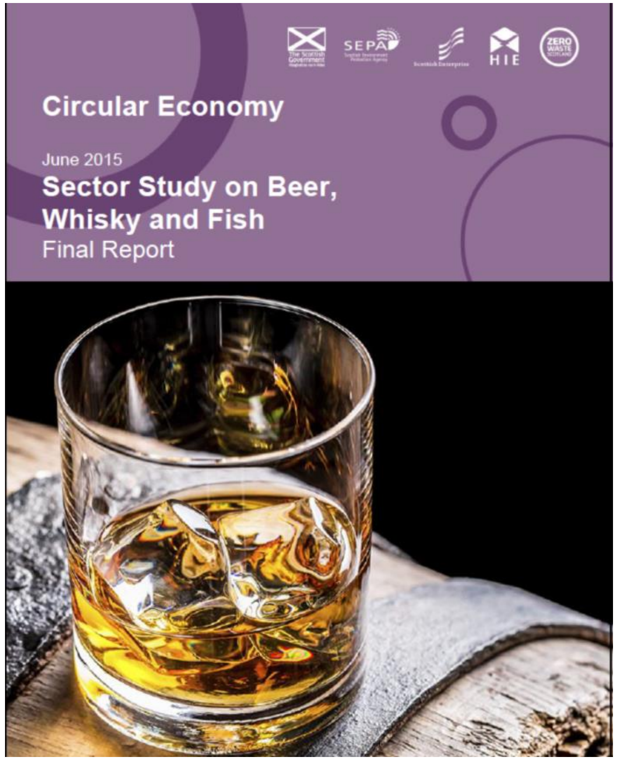
1.5 mn
distillery visits

Courtesy of Ronald Daalmans, Chivas Brothers

Stakeholder engagement developing methods for recovery of copper from a distillery wastestream

SCOTCH WHISKY INDUSTRY
Environmental Strategy

September 2016



Reducing our energy use and greenhouse gas emissions:

Responsible Water Use:

Embracing a 'circular economy' in our supply chain:

Sustainable land use:

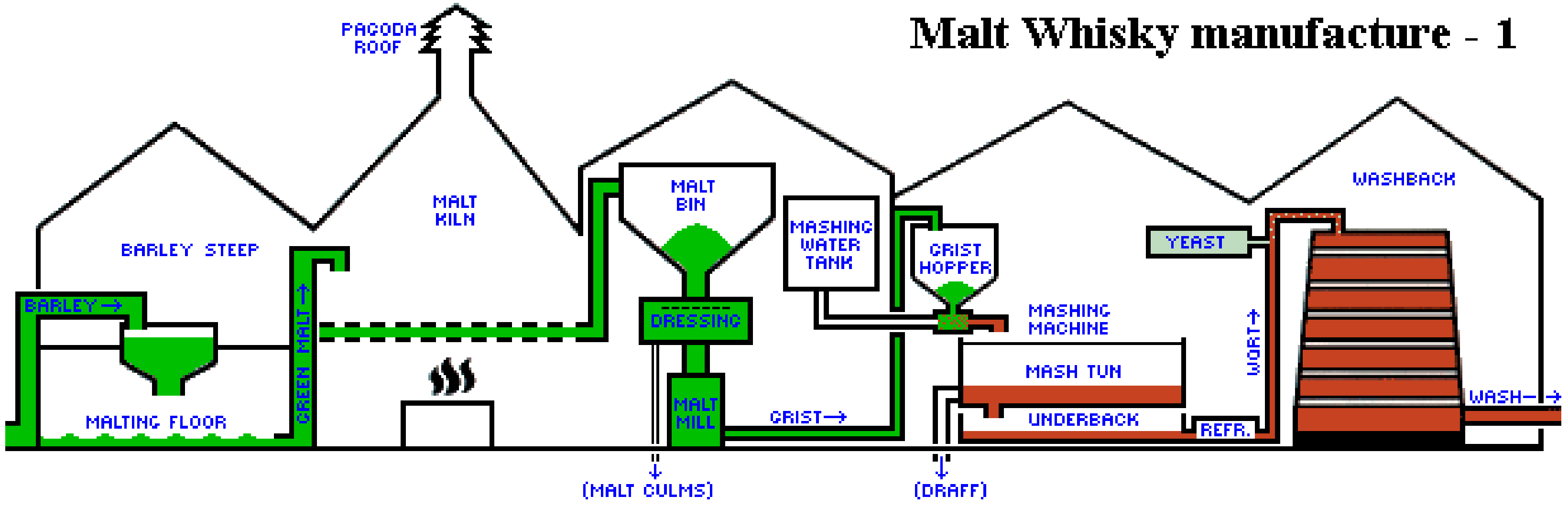
https://consult.scotland.gov.uk/zero-waste-delivery/making-things-last/supporting_documents/ZWS645%20Beer%20Whisky%20Fish%20Report_0.pdf

www.scotch-whisky.org.uk

Stakeholder engagement developing methods for recovery of copper from a distillery wastestream

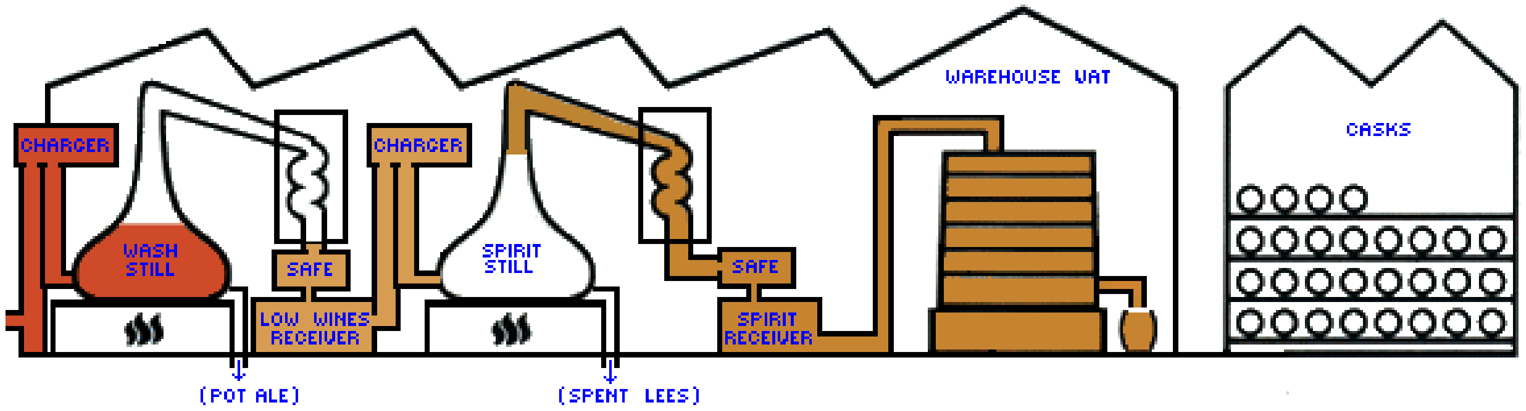
Chivas Brothers
Pernod Ricard

Malt Whisky manufacture - 1



Malting | Mashing | Fermentation

Malt Whisky manufacture - 2

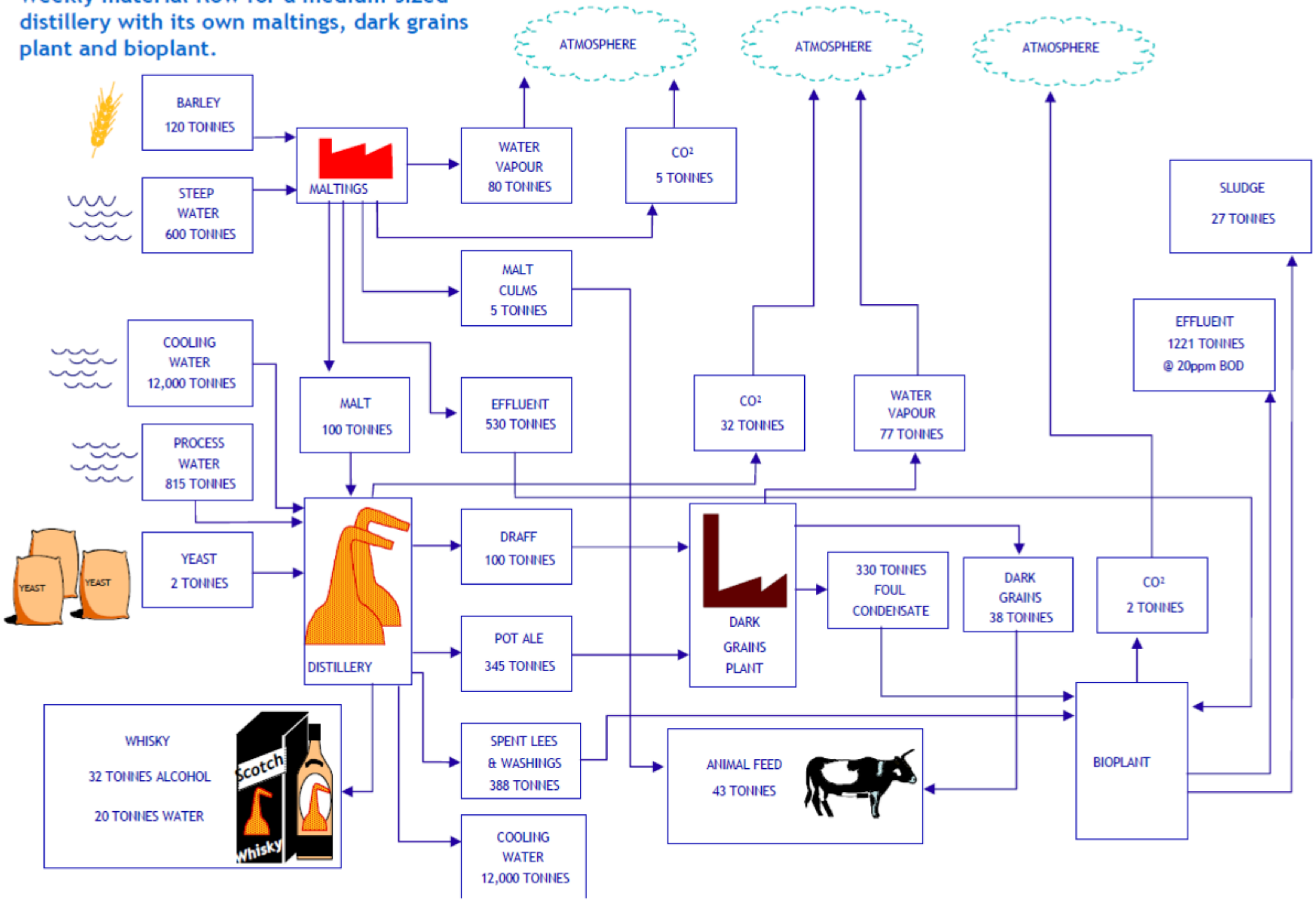


Distillation | Warehousing and Maturation

http://www.dcs.ed.ac.uk/home/jhb/whisky/glossary.html

The Malt Whisky Distilling Equation

Weekly material flow for a medium-sized distillery with its own maltings, dark grains plant and bioplant.



Courtesy of Ronald Daalmans, Chivas Brothers

The Malt Whisky Distilling Equation

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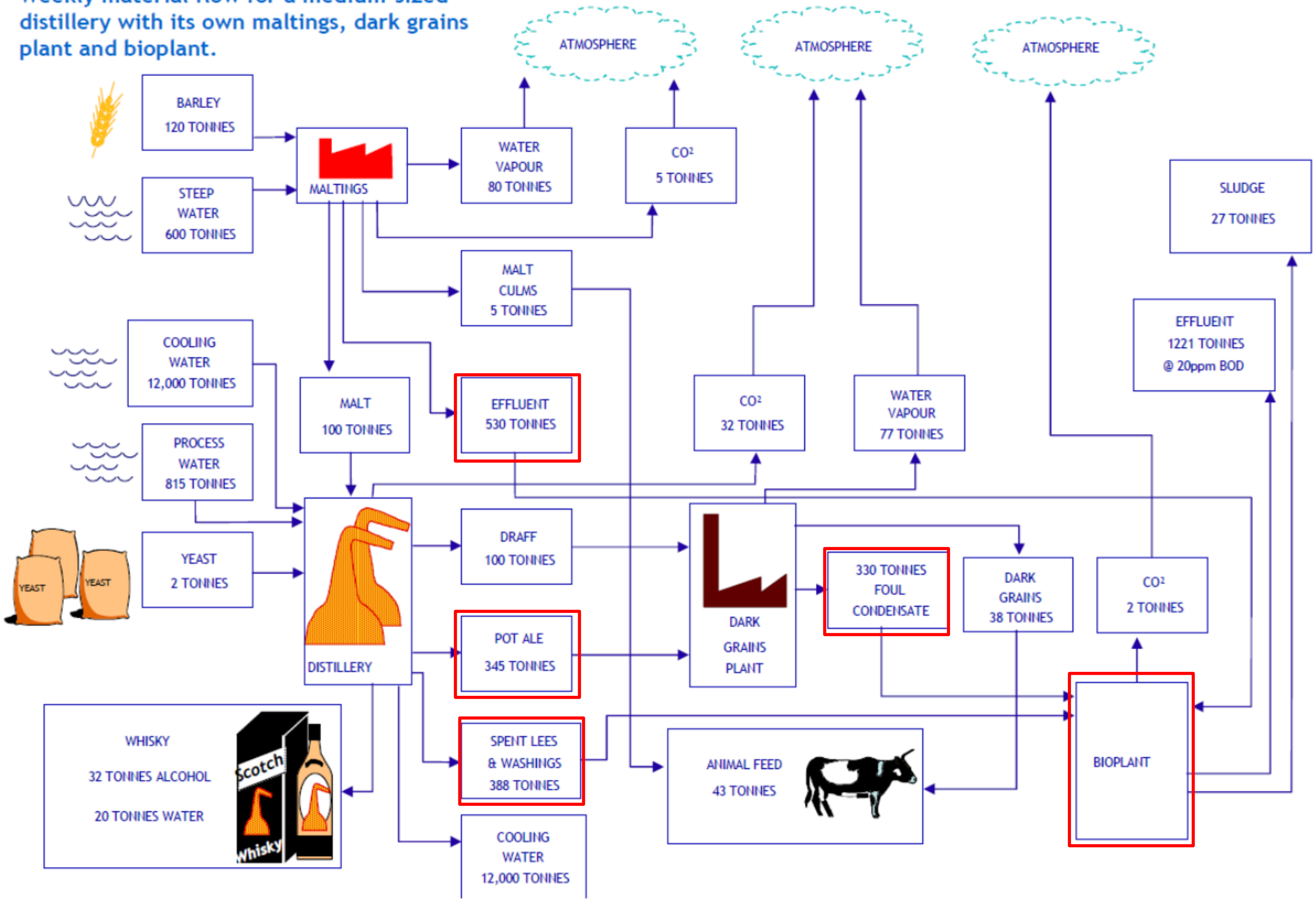


Courtesy of Ronald Daalmans, Chivas Brothers

Recovery of copper from a distillery wastestream with bioelectrochemical systems

Courtesy of Ronald Daalmans, Chivas Brothers

Recovery of copper from a distillery wastestream with bioelectrochemical systems

- Spent Lees from 6 different distilleries provided by Chivas Brothers

Dalmunach whiskey distillery

Dalmunach copper stills

Courtesy of Ronald Daalmans, Chivas Brothers

Spent lees from 6 different distilleries

Spent lees (SL) batch	$[Cu^{2+}]$	Conductivity	pH	COD	BOD_5	TOC	[EtOH]
	ppm	µS/cm		mg/L	mg/L	mg/L	% (v/v)
Dalmunach SL1	41.3±0.2	164	4.28	1442±40	1017	337±3	0.05
Dalmunach SL2	17.8±0.3	-	-	1302±7	900	394±15	0.05
The Glenlivet SL1	35.9±0.1	196	4.41	1565±11	1205	1062±6	0.12
The Glenlivet SL2	16.9±0.1	-	-	2362±13	1806	656±13	0.11
Glenallaachie SL1	11.7±0	-	-	1846±11	1356	556±4	0.08
Arberlour SL1	20.2±0	-	-	2304±4	1739	668±8	0.10
Tormore SL1	15.3±0.1	-	-	2206±9	1658	616±4	0.10
Allt-A-Bhainne SL1	11.8±0.5	-	-	1868±12	1450	548±19	0.07

Initial VFAs, anions and metals of Glenlivet SL1 (Rick Kimber, Manchester)

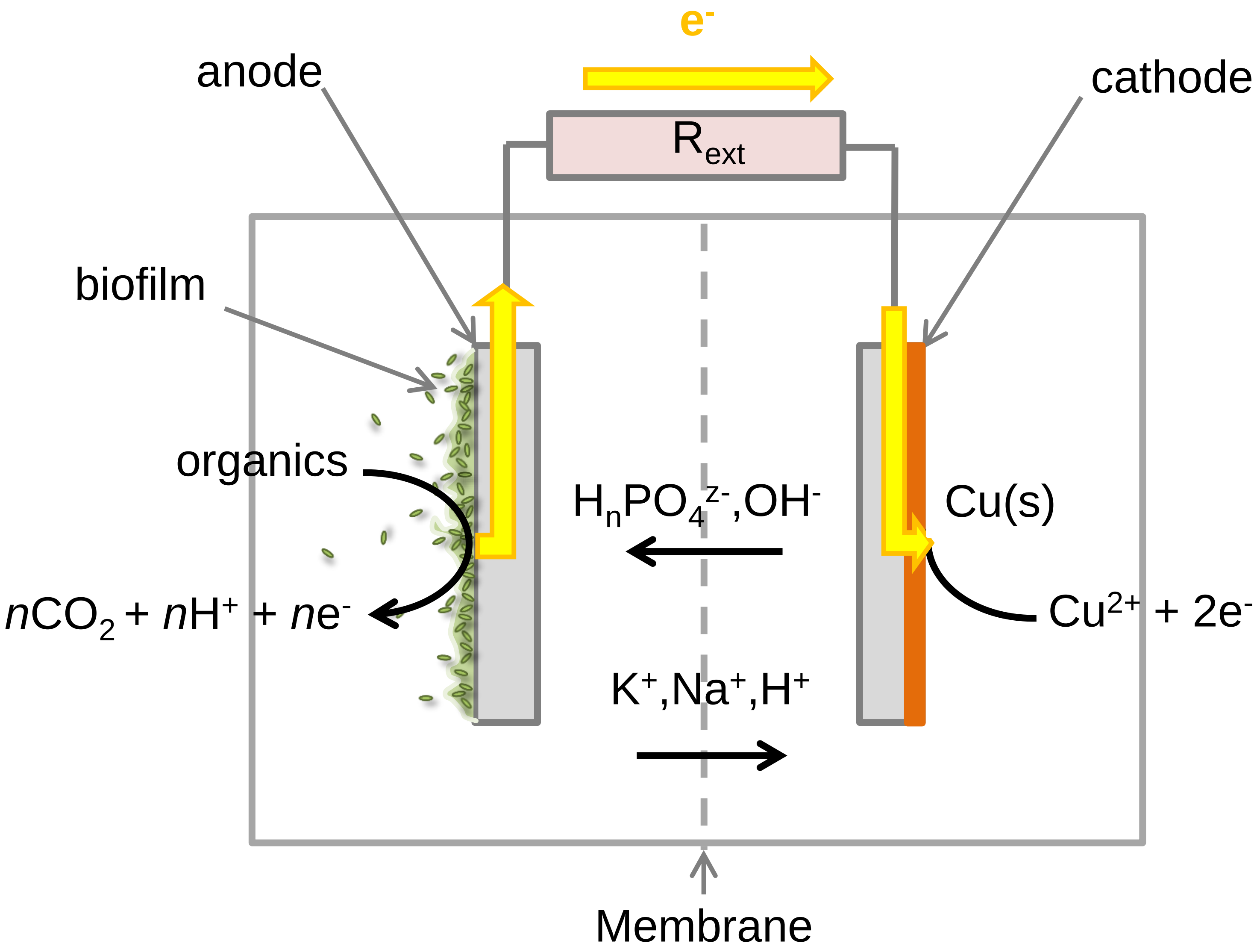
	Cu	Zn	Pb	Ni	Fe	Ca	Mg	Na
Average (mg / L)	27.4	0.3	0.1	0.0	0.6	0.1	0.2	0.0
STDEV	0.40	0.04	0.02	0.00	0.19	0.02	0.00	0.01

	Lactate	Acetate	Propionate	Formate	Iso-Butyrate	N-Butyrate	Iso-Valerate	Chloride	Nitrite	Nitrate	Sulphate	Phosphate
mg/L	14.4	55	1.8	0.6	2.9	1.4	1.3	6.3	0.2	0.3	15.7	21.9

Internal E determined by bomb calorimetry (Zhengxin Yao, Newcastle)

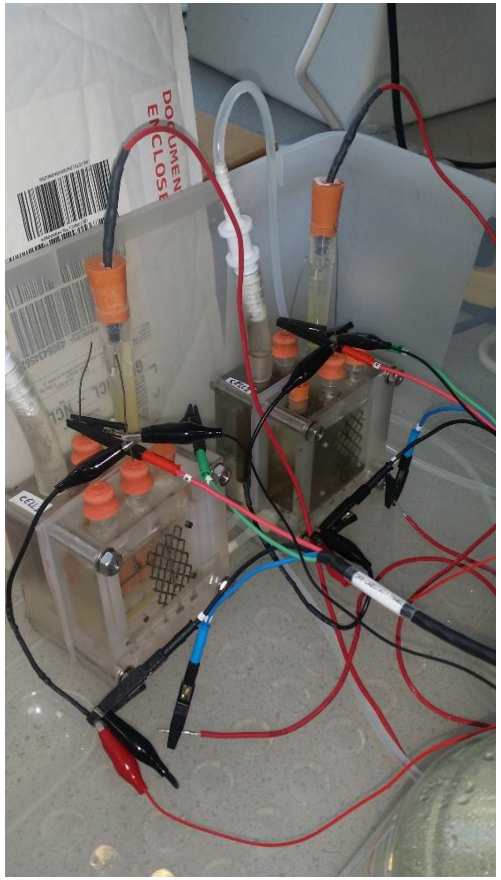
	Glenlivet SL1	**Domestic**
Energy (MJ/kg)	17.13	9.94
Energy (KJ/L)	26.56	12.94
KJ/g COD	13.85	19.31

Recovery of copper from a distillery wastestream with bioelectrochemical systems

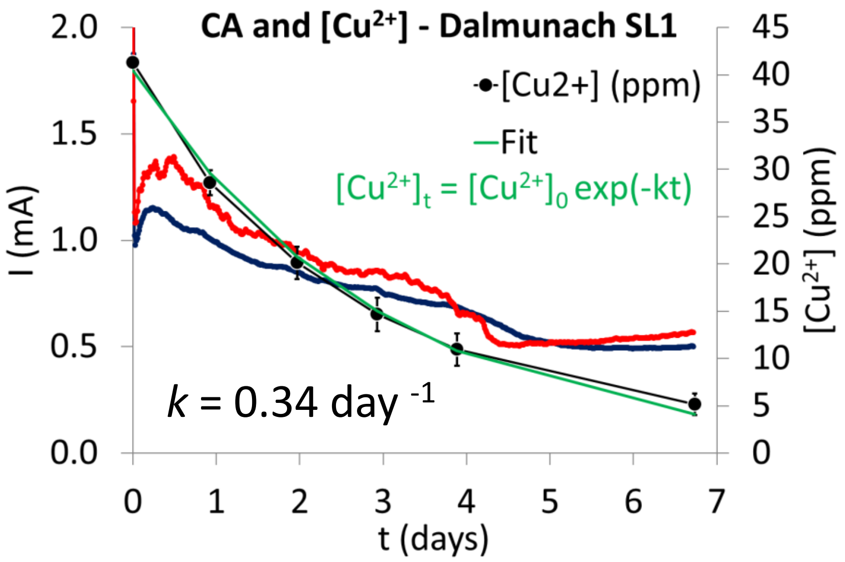


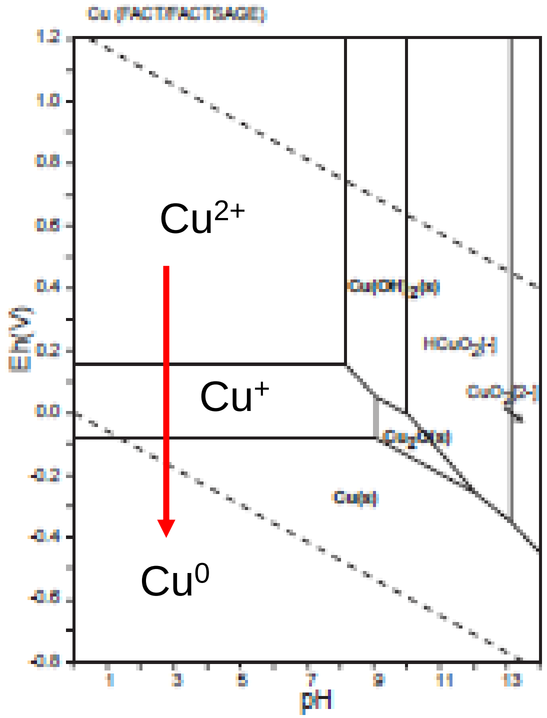
Recovery of copper from a distillery wastestream with bioelectrochemical systems

- Initial studies demonstrated feasibility of electrodeposition of copper from spent lees containing micromolar levels of copper



1.3 L of 'Spent lees' recirculated through 60 ml half-cell
Graphite plate WE poised at -0.4 V vs Ag/AgCl



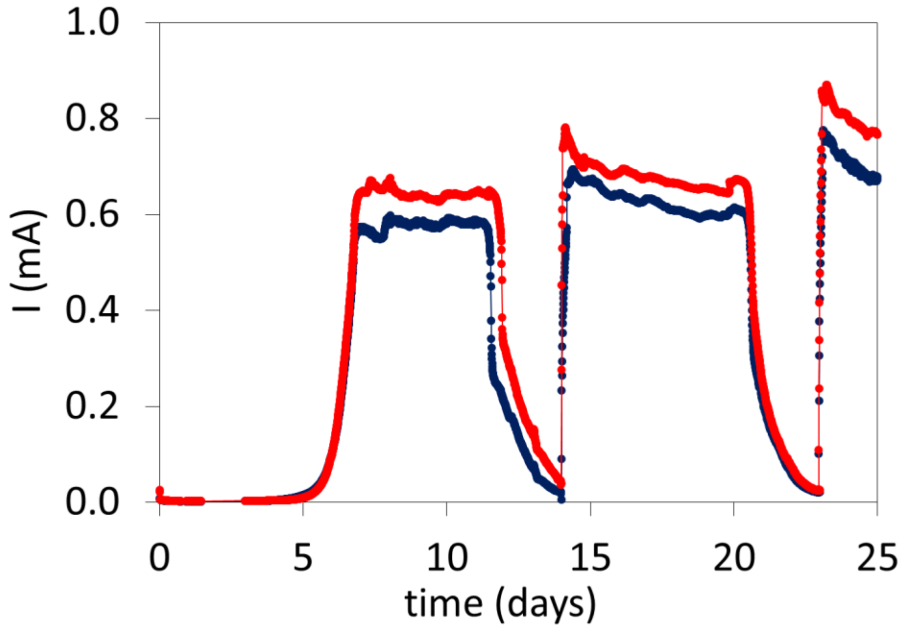


41±0 to 5±1 ppm
Cu^{2+} loss = 47±2 mg
Weight gain = 42±0 mg

Recovery of copper from a distillery wastestream with bioelectrochemical systems

- BES set up with an acetate-fed bioanode and copper removal from spent lees at the cathode

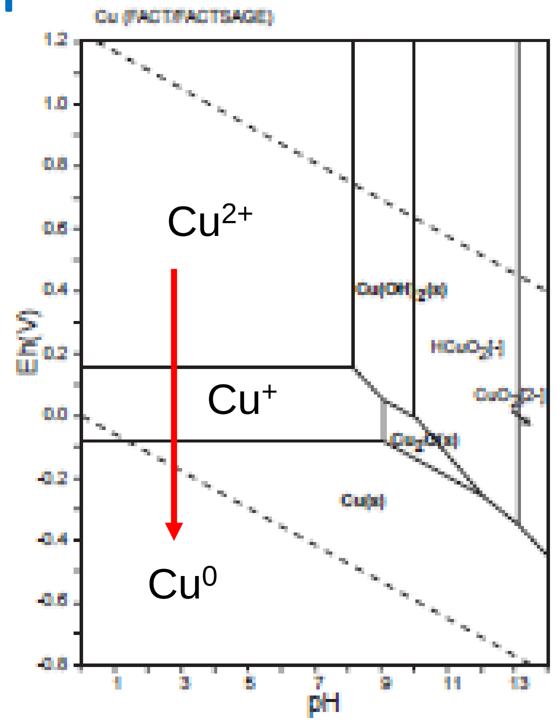
- AEM separator
- Operated as MFC or MEC
- MFC mode over a low external resistance
- MEC mode with a +0.5 V input from a power source



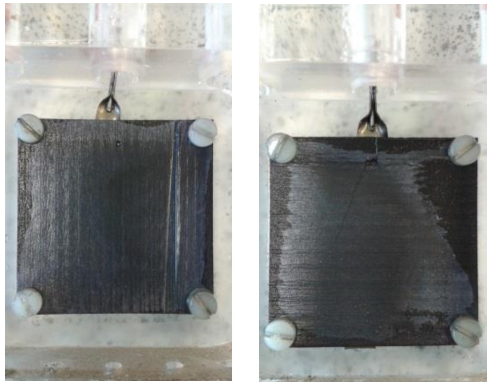
Electricity generation from the bioanode from Cu-reducing BES

Recovery of copper from a distillery wastestream with bioelectrochemical systems

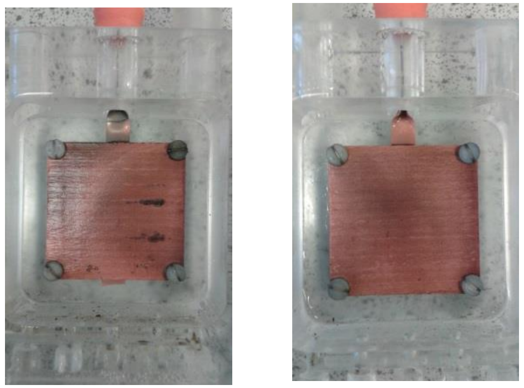
- BES set up with an acetate-fed bioanode and copper removal from spent lees at the cathode



MFC mode
R_{ext} = 10 / 0.5 ohms



MEC mode
Input voltage of +0.5 V



Dalmunach SL1

-91 ± 59 mV → Change in cathode potential → -434 ± 73 mV

Arberlour SL1

7 days at 10Ω then 3 days at 0.5 Ω

7 days with 0.5 V voltage input

36.6 ± 0.7 mg weight gain

16.1 ± 0.5 mg weight gain

37.3 ± 1.1 mg loss from solution (41±0 to 11±1 ppm)

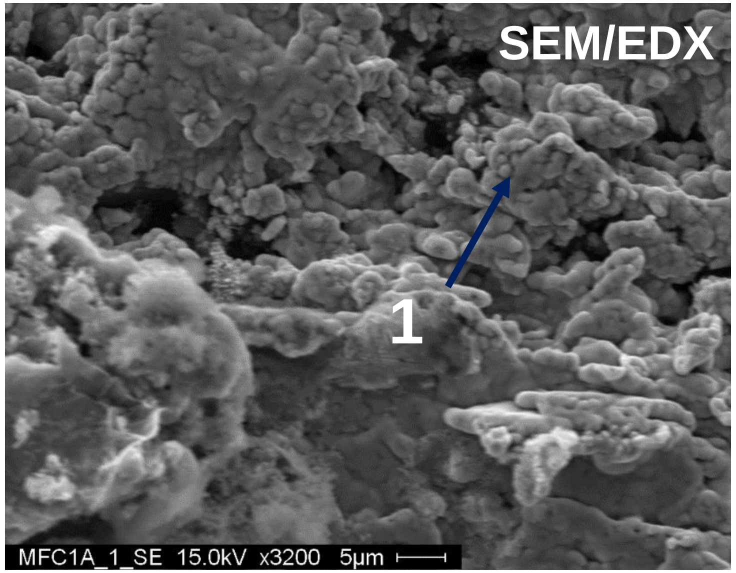
20.1 ± 0.6 mg loss from solution (20±0 to 3±0 ppm)

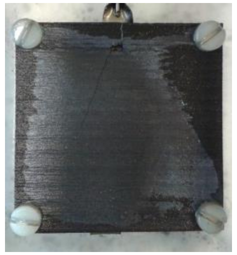
Current = 0.31 ± 0.16 mA

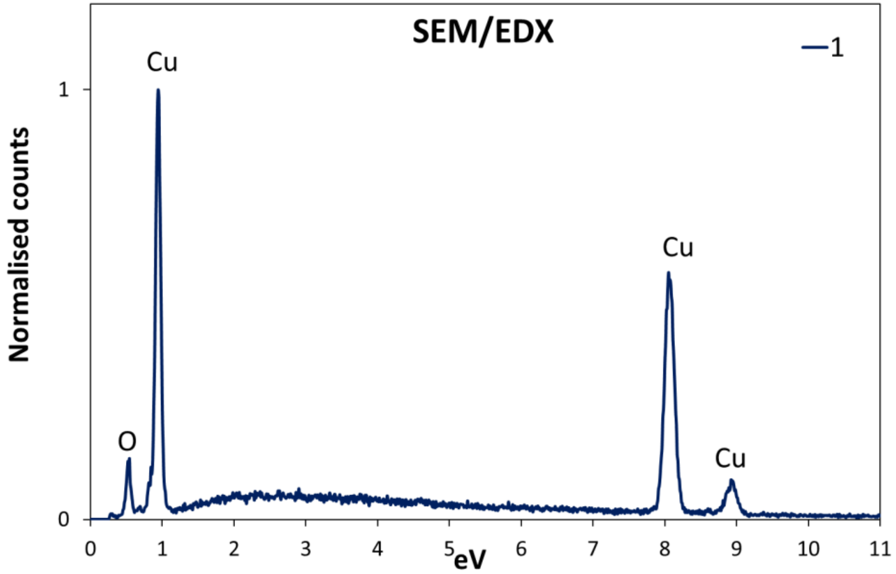
Current = 0.28 ± 0.10 mA

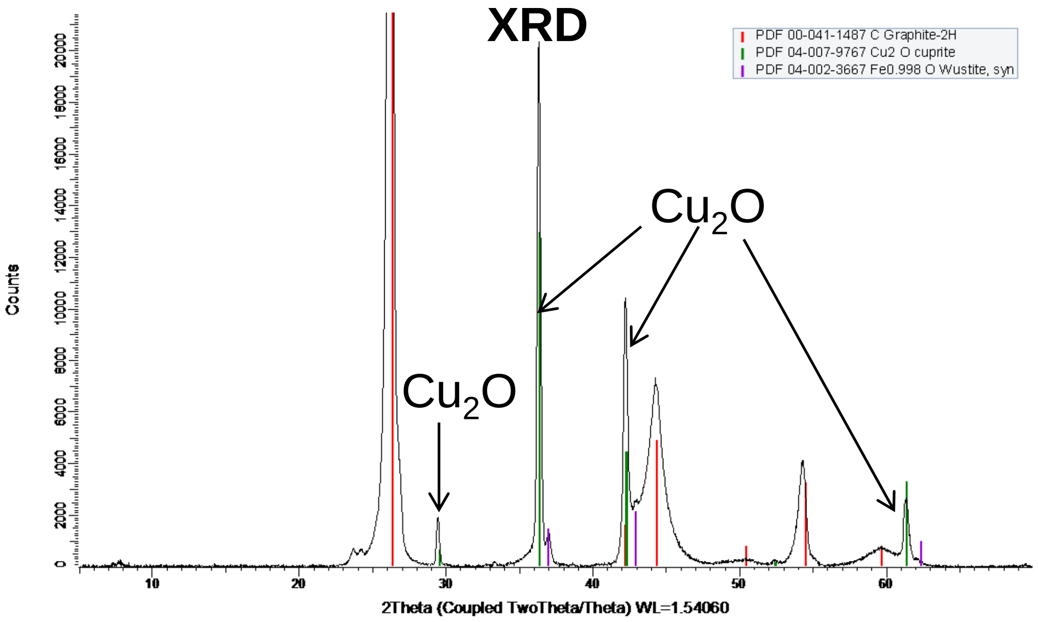
Recovery of copper from a distillery wastestream with bioelectrochemical systems

MFC mode









SEM with EDX

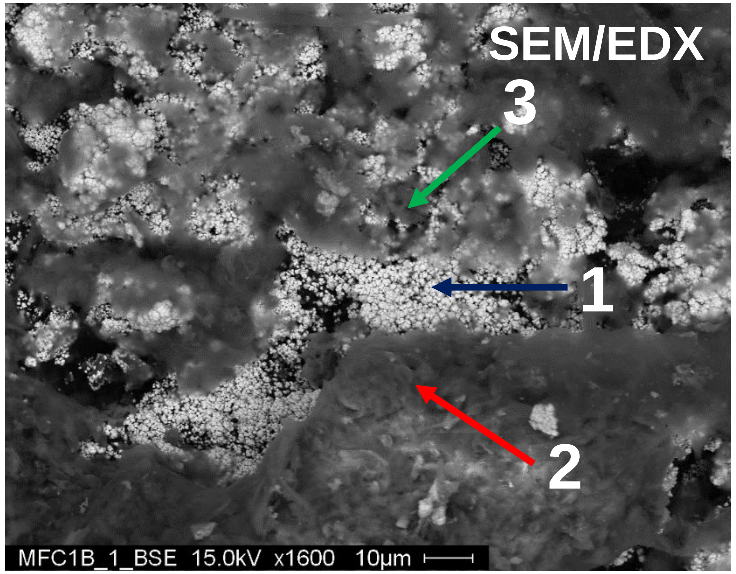
- Cu oxide

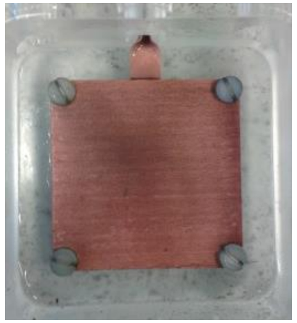
XRD

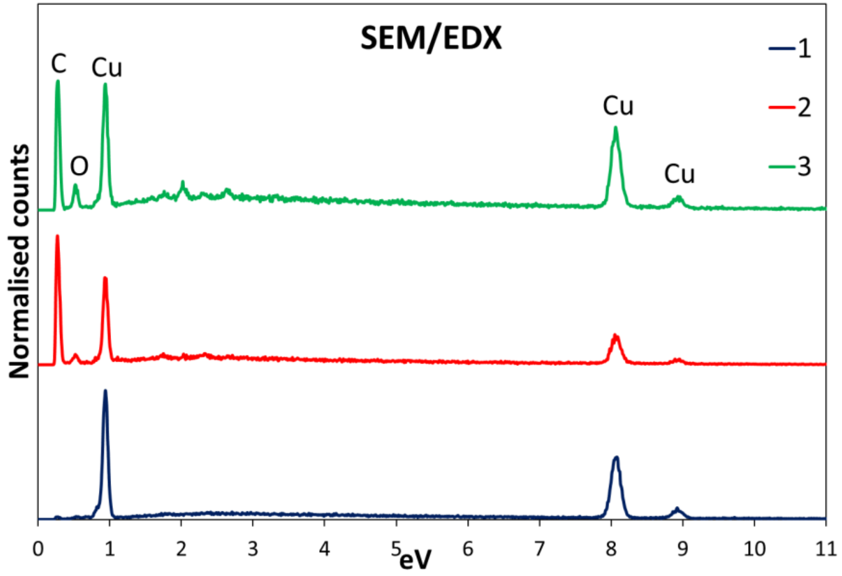
- Cu_2O (cuprite)

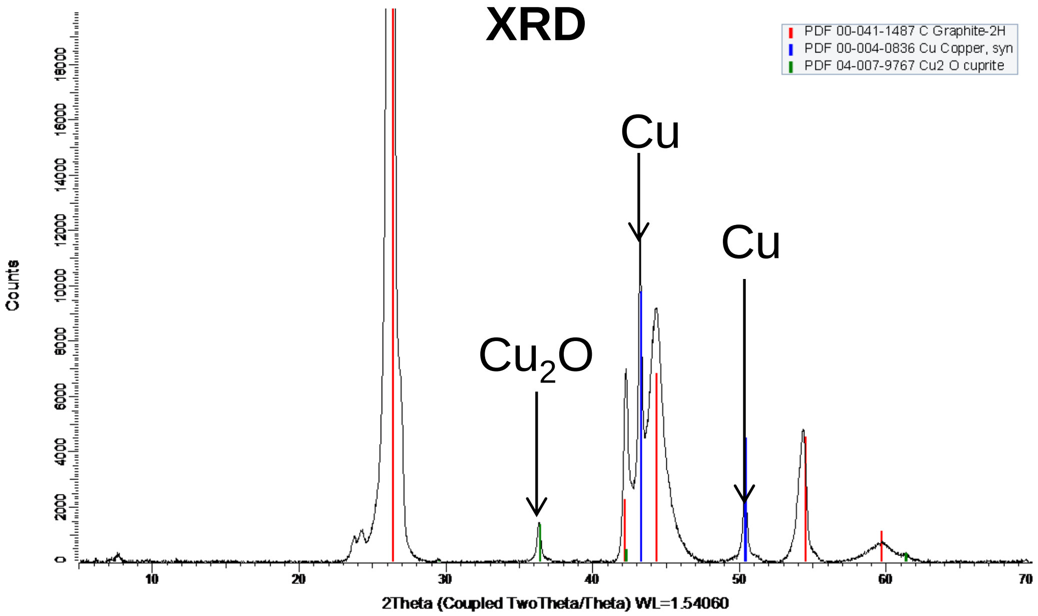
Recovery of copper from a distillery wastestream with bioelectrochemical systems

MEC mode









SEM with EDX

- Cu and Cu/O/C

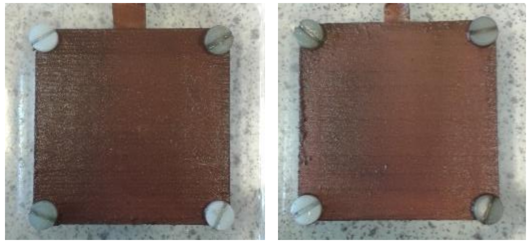
XRD

- Cu dominant peaks
- Cu_2O minor peak

Recovery of copper from a distillery wastestream with bioelectrochemical systems

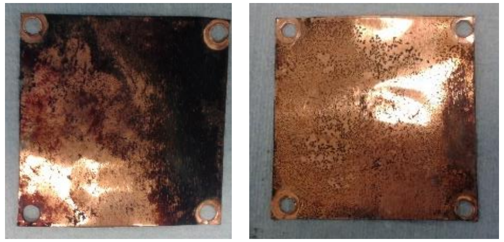
- Different cathode material can improve kinetics and allow Cu removal down to sub ppm levels.

Graphite plate



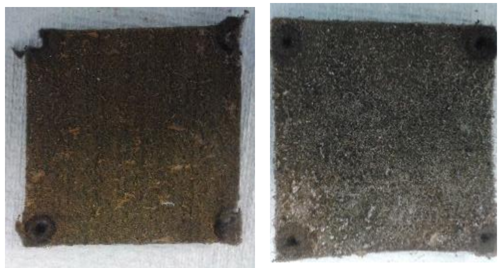
Weight gain = 14±1 mg

Copper foil

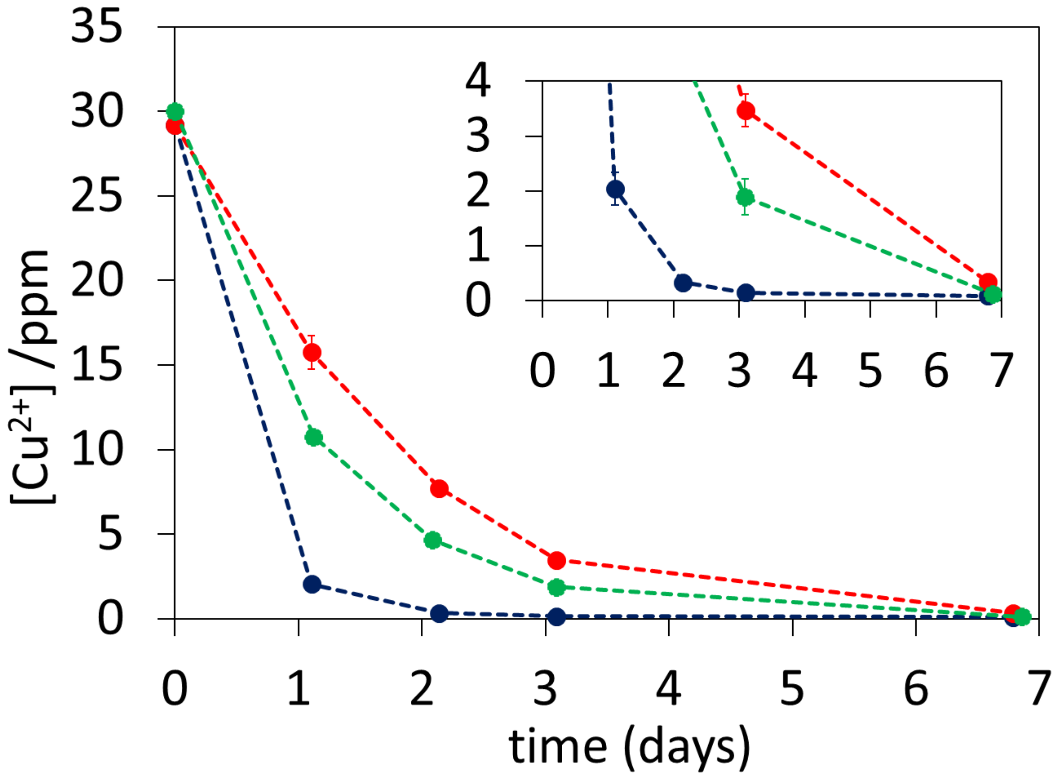


Weight gain = 15±0 mg

Graphite felt



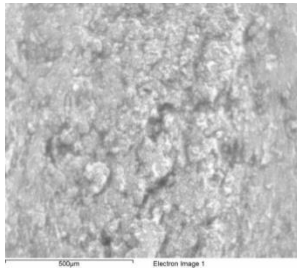
Weight gain = 54±19 mg



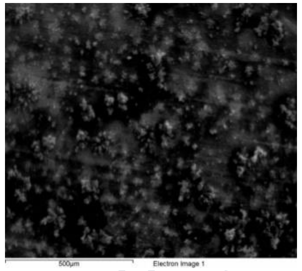
Recovery of copper from a distillery wastestream with bioelectrochemical systems

- Different cathode material can improve kinetics and allow Cu removal down to sub ppm levels
  - Enhanced removal but recovery of metallic copper may be compromised
  - Kinetics/recovery data incorporated into LCSA

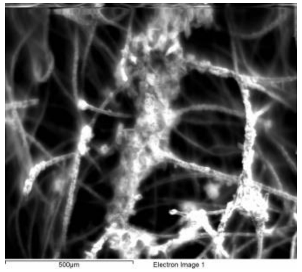
Graphite plate

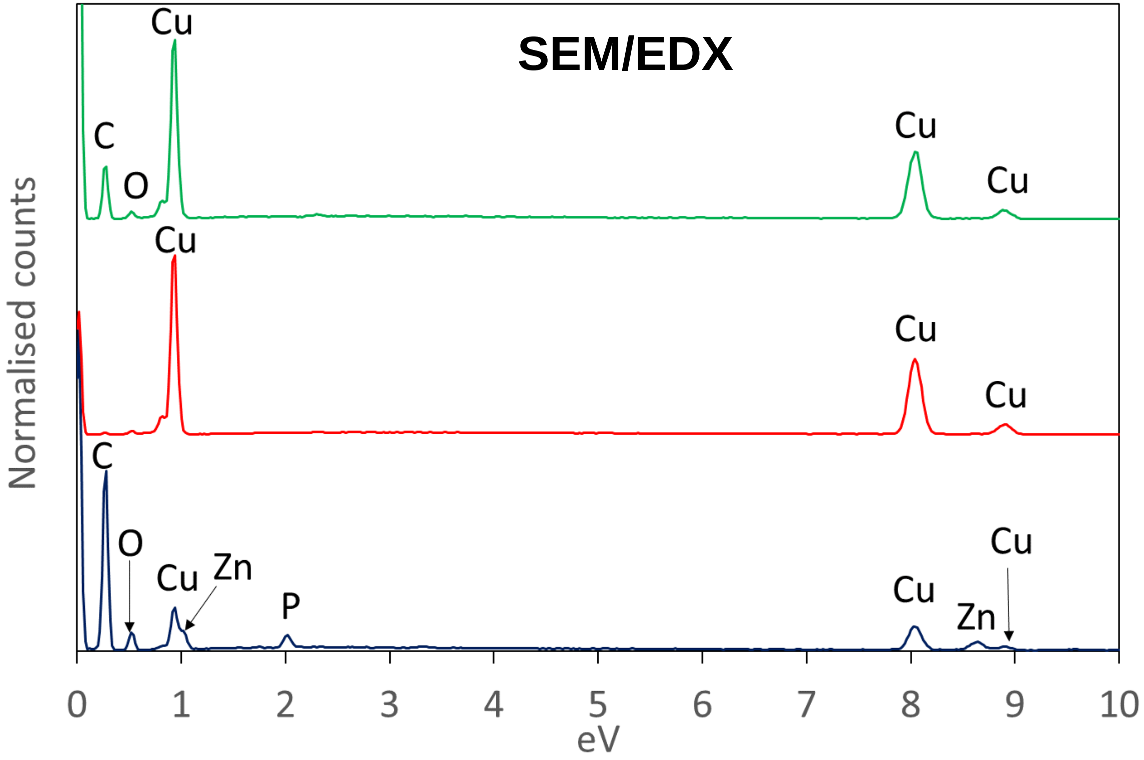


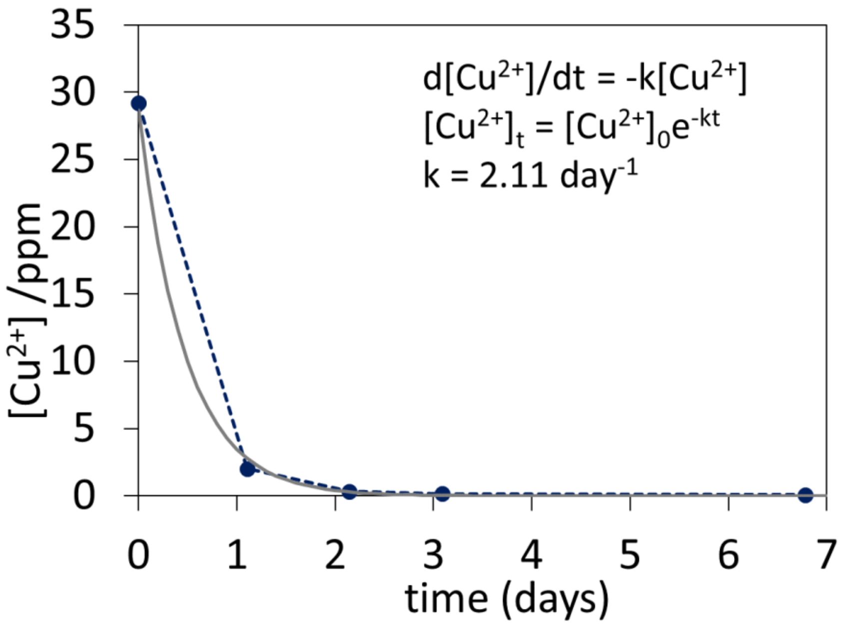
Copper foil



Graphite felt







Outputs and future developments

Resources, Conservation and Recycling 113 (2016) 88–105

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

A multilevel sustainability analysis of zinc recovery from wastes

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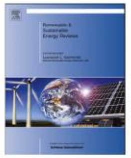

A critical review of integration analysis of microbial electrosynthesis (MES) systems with waste biorefineries for the production of biofuel and chemical from reuse of CO_2

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- Papers in preparation
  - Recovery of copper from distilling wastewaters and treatment to sub ppm levels using bioelectrochemical systems
  - Production and characterization of *Shewanella oneidensis* Cu^0 nanoparticles
  - Bioelectroprecipitation a novel route for Zn removal from aqueous wastestreams
  - Upscaling and LCSA of BES copper removal and recovery technologies
- Several conference and user-focused meeting presentations

Outputs and future developments

- *Successful bids*
- ***LifesCO_2R project.*** EPSRC. Eileen Yu and Keith Scott PIs with members of the MeteoRR team
- ***Design of an integrated waste management system for the whisky distilling industry; resource recovery and utilisation for cost, carbon and environmental footprint reduction.*** IAA project. Eileen Yu Scott PIs with Chivas Brothers and other members of the MeteoRR team
- ***Online Microbial Fuel Cell biofilm-based BOD sensor.*** Ian Head PI with Iano Premier and WH Partnership (MeteoRR team members). BBSRC-Innovate UK biofilms programme
- ***An online Microbial Fuel Cell-based BOD sensor for improved management of water quality.*** Ian Head PI with Iano Premier, WH Partnership and Northumbrian Water (MeteoRR team members). Internal Newcastle University funding
- *Unsuccessful bids*
    - **Innovative development of microbial fuel cells for monitoring BOD levels in real wastewater.** NERC Innovation fund.