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# From petrochemical complexes to biorefineries? The past and prospective co-evolution of liquid fuels and chemicals production in the UK

Simon J. Bennett\*, Peter J.G. Pearson

Centre for Energy Policy and Technology, Imperial College London, 311 Mechanical Engineering Building, London SW7 2AZ, UK

## A B S T R A C T

A debate has begun on the potential for renewable raw materials (RRM) to substitute fossil hydrocarbons in synthetic products. A related debate has arisen in the liquid fuels sector with contested proposals for the expansion of bio-fuels production. A transition to *integrated biorefineries* as analogues of oil refineries has been advocated, to enable RRM to compete with petroleum and minimise environmental impacts. Transitions between technological systems involve evolutionary processes, in which change emerges from reinforcing feedbacks between different levels of the socio-technical system. The past both shapes the current system and influences and constrains future options and pathways. Thus, over the past half century oil refiners and the associated petrochemical industry have achieved a high level of integration that challenges the competitive development of RRM, for which the full range of necessary technologies and product families are not well established and the commercial and technical risks are high. This paper explores a case study of the transition from coal-based to petrochemical feedstocks in the UK (1921–1967), applying a system dynamics approach to extract and elucidate the key interrelationships between technologies, policy and society. The findings and insights are then used to inform a discussion of scenarios for future biorefinery technologies, with a focus on bio-based chemicals.

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**Keywords:** Biorefinery; Multi-level perspective; Transition pathways; Renewable raw materials; Green chemistry; System dynamics

## 1. Introduction

Biorefinery ideas and initiatives are discussed increasingly in several literatures about cleaner energy, greener chemistry, process engineering, forestry, management and others. Most ideas arrive fully formed, portraying a novel design or technique for a biomass processing facility that has yet to be built and proved. While most such facilities have yet to receive financial support or even proof of concept, numerous less complex plants are being constructed to transform biomass feedstocks into saleable fuels, chemicals, fibres or feed; this makes the *integrated biorefinery* appear a more long-term ambition. Relatively little attention has yet been paid, moreover, to the industrial dynamics of biorefinery development, and how existing interdependencies between firms, infrastructure

and research objectives might shape or constrain biorefinery design. This paper discusses transition pathways to industrial use of renewable raw materials, building on insights from innovation theory and an exploration of the history of petrochemicals production.

The European chemical and fuels industries are being pressed to consider alternative raw materials for the future, for at least two reasons. Concerns about high current feedstock costs and potential oil supply constraints have instigated a debate about the sustainability of petroleum-based products. Environmental concerns and an eastward migration of bulk chemical production have likewise raised the attractiveness of renewable raw materials (RRM) based on biomass. The sustainability of some biofuels has been challenged in several recent scientific and political publications,

\* Corresponding author. Tel.: +44 20 759 47314.

E-mail address: [simon.bennett04@imperial.ac.uk](mailto:simon.bennett04@imperial.ac.uk) (S.J. Bennett).

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presenting questions about whether and how to support their future development (EAC, 2008a,b; Fargione et al., 2008; Mitchell, 2008; RFA, 2008; Searchinger et al., 2008). It is increasingly being suggested, moreover, that the greatest environmental, economic and social benefits might be achieved by the use of *non-food* biomass resources, exploitation of the whole feedstock and, where possible, production of high value co-products.

The *integrated biorefinery* concept encapsulates this approach. Thus, Ragauskas et al. (2006) propose ‘a total integration of innovative plant resources, synthesis of biomaterials, and generation of biofuels and biopower’, leading to biorefineries that will parallel modern oil refineries. Koutinas et al. (2007a) consider such biorefineries to entail the ‘economic conversion, fractionation, or extraction of a spectrum of biomass sources through integrated physical, biological and chemical processing for the production of various commodities and specialities’. This corresponds closely to a working definition of the biorefinery used by the IEA Task 42 Working Group and the EU Biopol project (Biopol, 2007).

Nevertheless, such broad definitions and analogies with petrochemical refineries provide limited guidance as to likely future plant designs and profitable technology/product combinations.

Thus, Sammons et al. (2008) and Chamboost and Stuart (2007) have recognised a problem of complexity, related to optimal product allocation, given that the full range of necessary technologies and product families is not well established. And, although Meiser et al. (2008) present a commercial strategy for managing some of the associated risks to enable RRM to compete with petroleum and minimise environmental impacts, in our view, the literature has paid insufficient attention to how current research, design and policy activities might influence the longer term application of biorefinery technologies. We also believe that lessons and insights can be drawn from the analysis of previous technological transitions.

Consequently, this paper aims to explore the potential for and the constraints on a transition to a new technological basis for chemical and fuels production built on bioresources. In doing so, it draws on the growing volume of recent research on technological transitions, which has been increasingly applied to policy formulation for sustainability. It applies this analytical approach to the exploration of previous transitions, in search of insights into the factors and interactions that might advance or retard the prospective co-evolution of fuels and chemicals production in the UK and the development of biorefineries.

The paper has the following structure. Section 2 outlines the socio-technical theories relevant to the introduction of renewable raw materials (RRM), while Section 3 sets out the empirical approach taken in this paper to applying them to an earlier relevant transition, the introduction of petrochemicals in the UK up to 1967. Section 4 presents key results of this research. Section 5 then uses the insights gained from this qualitative study to inform a discussion of possible futures for RRM in the UK. Section 6 concludes the paper.

## 2. Theoretical background from the innovation literature

Transitions between technological systems have been characterised as evolutionary processes, in which change emerges from the selection of new technologies that fit with socio-economic criteria relating to performance, cost, familiarity and changing user preferences. This is an approach that embraces concepts from several parts of the literature on innovation, including *bounded rationality*, *diversity*, *selection*, *path dependency* and *lock-in*, and *co-evolution* (Van Den Bergh et al., 2006). Thus, reinforcing feedbacks between different ‘levels’ of the socio-economic system are seen as enabling novel technologies, or combinations of technologies, to diffuse into the economy and ultimately to displace existing technologies and practices, or to themselves be overtaken and disregarded. One

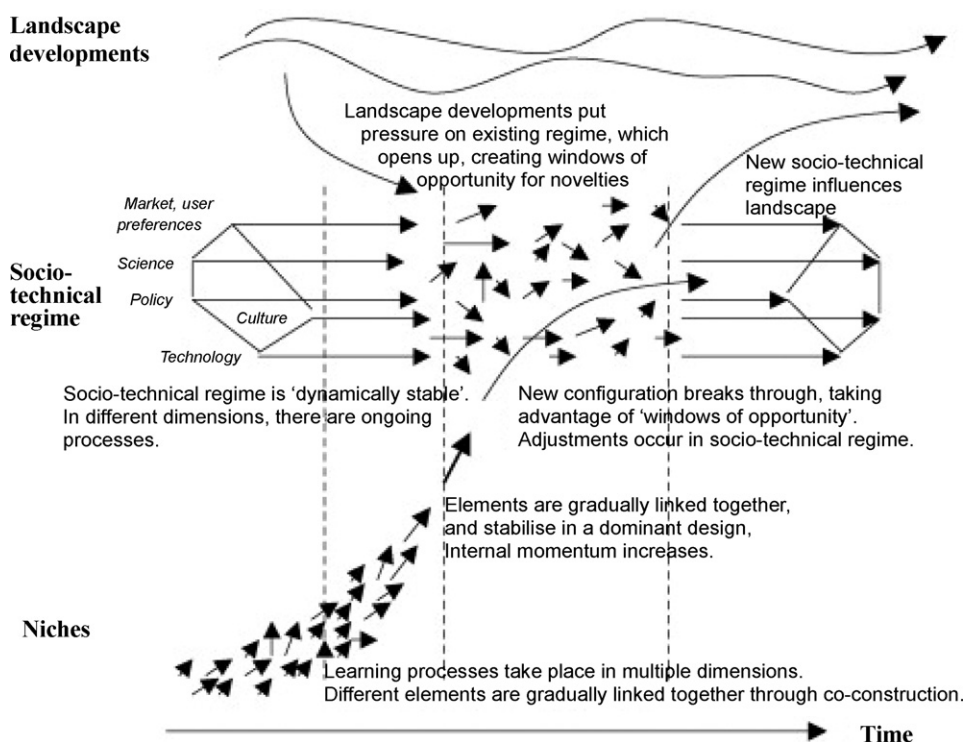


Fig. 1 – Multi-level framework for the analysis of socio-technical transitions. Adapted from Geels (2002).

approach to the analysis of transitions considers three such 'levels' and has been labelled as the Multi-Level Perspective (MLP) (Geels, 2002), illustrated in Fig. 1.

At the *micro* level *niches* are seen as providing the initial applications for a given technology, usually in areas where its particular characteristics are especially advantageous, and sometimes while receiving protection from a regulatory or performance standard. Relief from direct competition with incumbent technologies enables users and producers to become familiar with innovations and to engage in cost-reducing learning processes; it also allows supply chains and other supportive social networks to become established. Examples of policy protection include that given to first generation biofuels, which would otherwise be uneconomic, or the use of biorenewable plastic bags for organic waste collection—a niche application in which low barrier performance is outweighed by biodegradability. Social networks such as supply chains can be constructed and are built in niches. At the *macro* level a *landscape* is conceived that represents the broader political, social and cultural values and institutions that form the deep structural relationships of a society. The landscape changes slowly over time and exerts a selection pressure on new technologies, in terms of the general political environment, prevailing economic trends, and social attitudes regarding, for example, environmental protection. Changing societal attitudes towards climate change are a contemporary example of a changing landscape.

At the *meso* level a *socio-technical regime* includes the producers, the users and the material elements of the technologies themselves. Rip and Kemp (1998) describe these as the "engineering practices; production process technologies; product characteristics, skills and procedures [...] all of them embedded in institutions and infrastructures", that create and reinforce a particular technological system. In a technological transition the regime can be seen as the variable undergoing change. Changes at the niche level (emergence of innovative technologies) or at the landscape level (geopolitical events or trends) can act to disrupt a relatively stable regime and create opportunities for the new technology to become more widely adopted (see Fig. 1). For example, the development of novel biodegradable chemicals from RRM could provide 'upwards' momentum, whilst greater environmental consciousness amongst consumers is an example of possible 'downward' pressure. In this framework, the success of a new technology is not seen as guaranteed and depends to a large extent on whether and how it diffuses and becomes stabilised by new infrastructure, social networks and synergistic technologies; but an opening or 'window' in an existing regime can create breathing space in an otherwise initially hostile commercial environment.

By treating regimes as dynamic variables undergoing change and influenced by both landscape and niche level developments, application of the MLP has provided insights into the processes of technology adoption in, among others, electricity networks (Verbong and Geels, 2007), biogas energy (Geels and Raven, 2007), personal road transport (Geels, 2005) and non-food crops policy (Bos et al., 2008). The present paper extends previous empirical work to the field of basic organic chemicals and considers the multi-regime dynamics that influence change in the field of fuels and chemicals.

While an agreed definition of a regime has yet to be developed in the literature, we follow Geels and Schot (2007) in focusing on the level of the scientists, policy makers, entrepreneurs and special-interest groups that share a set of

rules arising from their 'routines', heuristics, networks, legislation and the inflexibility of their physical and economic assets. In this paper, we define and analyse two distinct, but interrelated, socio-technical regimes that fulfil separate societal functions (Konrad et al., 2008): the *Organic Chemical Production Regime* and the *Liquid Fuels Production Regime*. Both are described briefly below.

Firstly, the organic chemical industry can be regarded as a distinct regime because of its extremely high levels of interconnectedness: whilst the products of this global industry serve a multiplicity of societal demands, it draws on a shared educational base, common practices, united political advocacy, connected management and capital, and political accounting that groups the industry's products by established classifications.<sup>1</sup> This interconnectedness enables a consideration of the related changes in feedstock use that might disrupt the basis of the industry, but would probably do so unequally across its functional outputs.

Secondly, the production of and institutions associated with gasoline, diesel and novel bio-based liquid fuels can be viewed as a distinct regime, not least by virtue of the industry's historical corporate structure. The vertical integration of the major firms from well-to-pump has generated political and institutional structures that unite actors involved in the provision and use of liquid transport fuels.

Over the past half century these two regimes have achieved a high level of integration of processes and industrial ownership, supply chains and governance, developing the efficiency and cost advantages of mature technical systems, established human routines, and co-located infrastructure. The two regimes have together influenced the patterns of current organic chemical feedstock use. Research by Raven (2007) and Konrad et al. (2008) has recognised the significance of the *co-evolution* of regimes in certain transitions, and chemical feedstocks appear to be an example of it. Co-evolution implies that the 'dynamics in one evolving system influence the selection environment in another' (Foxon, 2008; Murmann, 2003). This in turn suggests inter-sectoral interactions and suggests a particularly important role for feedbacks *between* regimes.

The advantages of co-evolution are also sought by biorefinery designers who recognise that co-production of several saleable products can generate cross-subsidies that make otherwise uncompetitive products viable. Theory suggests, however, that technological change involving feedback processes between the components of the techno-economic system is not a short-term reconfiguration process (Ruttan, 1997). This proposition is borne out by the experience of the oil industry, which took several decades to settle on profitable product mixes and utilisation of by-products by entering new industries. This example presents a clear challenge to the competitive introduction of RRM, since the development of new supply chains and institutions for bioresources could require unprecedented interactions between the biotech, agriculture, chemical and oil sectors.

The next section outlines our approach to elucidating the feedbacks that might underpin transitions to new feedstocks. We suggest that understanding these feedbacks could help focus policy and engineering research on exploring steps that might encourage the *evolution* of integrated biorefineries and

<sup>1</sup> For example, in the EU PRODCOM 'PRA.24.14 Organic Basic Chemicals' is the accounting code for almost all bulk organics regardless of end-use (EC, 2007).

of valuable interactions between the two regimes at niche, regime and landscape levels.

### 3. Methods

Several recent empirical studies of innovation for sustainability and of technological transitions have used mainly qualitative analysis. Researchers working with historical material have drawn primarily on literature sources and taken inspiration from social constructivism and evolutionary economics (e.g. Bijker et al., 1987; Murmann, 2003). Several studies have, however, used the MLP to structure empirical material and link technological diffusion from niche applications to issues of social expectations and compatibility with existing infrastructure (Geels, 2005; Raven, 2007; Verbong and Geels, 2007). These factors are typically difficult to represent and compute in quantitative economic models. A downside of this largely qualitative approach is that its narrative output is rarely finely enough grained to enable the underlying industrial dynamics to be accessed. Whilst the theory continues to be refined (e.g. Genus and Coles, 2008; Holtz et al., 2008), we agree with the contention that it is sufficiently robust to be extended to technology foresight (Shackley and Green, 2007). Two extensions are made to this work on electricity scenarios to explore more thoroughly how insights from the past might be mapped to a prospective transition; these extensions employ *process analysis of events* and of *system dynamics*, both of which are described below. Next, we outline a methodological approach to capturing the fundamental dynamics operating in given regimes and employ this approach in scenario-building for innovation for sustainability.

#### 3.1. Process analysis of events

In order to analyse the past dynamics of chemical feedstock choices, we have collected in a database records of key historical events related to developments in UK petrochemicals. The method is inspired by process analysis, as described by Van De Ven et al. (1999), and by the *system dynamics* literature. The process analysis method was originally developed for firm-level studies but has also been applied at system (regime) level (Negro et al., 2007). In our data collection we systematically identified and retrieved events (speeches/comments made, reports published, legislation passed, investments made, production trends, etc.) from:

- Official and unofficial histories of the firms involved (ICI, DCL, BP, Unilever, Shell, Dow, etc.).
- Government legislation and related publications (e.g. reports of the Monopolies and Competition Commissions).
- Contemporary academic articles and subsequent history studies (e.g. from *Annals of the Association of American Geographers*; *The Economic History Review*; *Journal of Industrial & Engineering Chemistry*; *Science Studies* and 5 others).
- Publications of learned societies (e.g. *Journals of the Chemical Society* and *Proceedings of the Royal Society of London*).
- History of technology literature (e.g. Galambos et al., 2006; Stratton and Trinder, 2000).
- Texts on political history texts (e.g. Grant et al., 1988; Jones, 1981).

Since two regimes of considerable importance are here identified as influencing the trajectory of chemical feedstocks

use, it was important to include events relating both to liquid fuels production and organic chemicals production. As noted earlier, the study of two regimes recognises the significance of *co-evolution*. The database approach provides for both regimes and their interactions ‘a coherent sequence of events and trends that describe how things changed over time’ (Negro et al., 2007).

Since it is the nature of feedstocks in their most general form that underpins the contemporary discourse on biorefineries and RRM (Chew and Bhatia, 2008; Grundberg, 2008; Kleinert and Barth, 2008; Koutinas et al., 2007b), it was considered necessary to include a wide range of sources. The system boundary for determining inclusion was kept temporally broad, from the late 19th century until the 1980s, so that the end-point was not inappropriately pre-determined. The events included were defined by their having some causal link to subsequent events within one or both socio-technical regimes; this therefore included relevant landscape changes and events in related regimes. To address elements of selection bias (George and Bennett, 2005), the extraction and processing of the pertinent details from this richness of resources was undertaken systematically by classifying events by date, regime and location and constructing sequences of causality between them.

Seventy-three distinct sources were searched for both quantitative and contextual data and 1311 events were catalogued. They range from speeches by captains of industry, to national policy decisions, to details of physical and financial investments made in research or production capacity.

#### 3.2. System dynamics and causal loop diagrams

Another methodological addition in this paper is a diagrammatic construction of the feedbacks that underpin the industrial dynamics. Scholars of innovation and systems thinking have frequently emphasised the importance of feedback effects (Fagerberg, 2003; Kline and Rosenberg, 1986). Modelling of feedbacks in operational research was developed in to a simulation discipline known as *System Dynamics*. System dynamics is commonly applied to management problems, and has also found application in the innovations literature regarding energy transitions (Struben and Sterman, 2008). Radzicki and Sterman (1994) and Wolstenholme (1982) provide an overview of system dynamics and its history in Operations Research, including a controversial early application to resource limits by the Club of Rome (Meadows et al., 1972).

The construction of qualitative ‘causal loop diagrams’ of feedbacks that present dynamic hypotheses about how the system components interact is a key element in the system dynamics analytical approach, and is employed here. These diagrams provide an interpretation of the structure of the system, which conditions how decisions are made. By making this structure explicit, these representations challenge any private mental models we hold for comprehension of complex social behaviour and technical interactions. Causal loop illustrations of historical behaviour have been recognised as a valuable tool for understanding the structure of systemic linkages and developing hypotheses about how the dynamics might operate (Coyle, 2000; Homer and Oliva, 2001). While continuation to quantitative simulation is sometimes appropriate (see Morecroft and Heijden, 1992; Morecroft, 2007 for examples) in this case the complexity, scope and difficulties of quantification in the relationships between chemical technologies and their societal context, made simulation inappropriate.

We follow Stermann's (2000) conventions for causal loop construction. Thus arrows indicate direct causal links through which 'information' flows. Where a positive sign accompanies the arrow then a change in the variable at the stem of the arrow will lead to a change in the variable at the head in the same direction but not necessarily by the same magnitude. For example, if driving increases positively, fuel taxes collected increase; if driving is reduced then fewer taxes are collected. A complete loop of positive arrows indicates a positive, or reinforcing, feedback which, in the absence of other countervailing influences, will continue to increase the magnitude of each variable in the loop. This is denoted by R.<sup>2</sup>

The user of causal loop diagrams faces the challenge of reducing the complexity of the structure to a tractable level whilst retaining sufficient detail to capture important relationships. The richer the structure the greater the challenge of linking the dynamic hypotheses to system behaviour. From a qualitative perspective, however, our experience has demonstrated that fully linked complex diagrams are laborious to decipher and may not ultimately provide the analyst or reader with a sufficient grasp of the resulting behaviour. The loops presented in this text are subsections of larger diagrams that are recorded elsewhere (Bennett, forthcoming). Because the construction of the causal loops is a process that can allow niches and transition phases to become more clearly apparent (Burchill and Fine, 1997; Luna-Reyes and Andersen, 2003), events in the database were not initially allocated to particular levels within the system, or to specific phases in the transition to petrochemical feedstocks in the UK, described in the next section.

#### 4. The transition from coal-based to petrochemical feedstocks in the UK (1921–1967)

##### 4.1. Overview

The global transition from coal-based chemical products to petroleum-based synthetic products was a rapid technological change that was initiated by the first mass-production of automobiles in the US at the beginning of the 20th century. Thus Ruttan (1997) writes that,

"beginning in the 1920s with the rapid growth in the demand for gasoline for automobiles and trucks in the United States, a large and inexpensive supply of olefins become available as a by-product of petroleum refining. By the end of World War II, the US chemical industry had largely shifted to petroleum-based feedstocks."

He notes, however, that,

"In Germany this transition – locked in by skills, education and attitudes that had been developed under a coal-based industrial regime – was delayed by more than a decade."

According to Stokes (1994),

"neither the changeover to petroleum-based feedstocks nor the pace of the transition was inevitable; rather, both depended on choices made by politicians and industrialists within the context of the political economy of the 1950s, as well as the context of prior German experience."

The introduction of petrochemicals in the UK began after the 1920s/1930s developments in the US, and before the 1950s/1960s developments in Germany (Ruttan, 1997; Stokes, 1994). Given that gasoline markets were developed in all three countries in the 1910s, and that the UK's chemical demand for coal gases did not reach the total available supply from coke ovens (Hudson, 1983), the reasons for the rapid take-off of petrochemicals in the UK at this particular time can reasonably be surmised to arise from industrial dynamics that were particular to the UK chemical industry and its interaction with the oil refining business.

In 1920 the UK organic chemical industry had two parts, a dyestuffs and pigments industry, and an infant industry for pharmaceuticals, detergents and biocides (Hardie and Davidson Pratt, 1966). Coal tar aromatic hydrocarbons were the dominant raw material. These 'aromatics' were plentifully available as by-products from the coke ovens of iron and steel works (Table 1 shows the difference between aliphatics and aromatics). There were no significant chemical products based on petroleum oil or gas in the UK.

By 1967 the entire organic industry had been totally transformed. Vast integrated sites had been erected in Stirlingshire, South Wales, Merseyside and Teesside for the conversion of imported petroleum into liquid fuels and organic chemical products (Chapman, 1992). Older products such as fertilisers and dyes were produced from the new raw material, and a vast range of new synthetic products became available from the oil-based feedstock, many of which were substitutes for natural products used in 1920, including rubber, wood and starch. Development of techniques for the commercial extraction of a BTX fraction from petroleum refining completed the transition from coal-based to petrochemicals.

Fig. 2 shows this transition from coal- to oil-based chemicals. It mirrors the substitution of coal by oil and gas in primary energy use, but, starting later, it shows a much more rapid overturn of the raw material base.

##### 4.2. Three phases

We have delineated three main phases of the transition. These are summarised as follows.


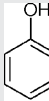
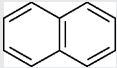
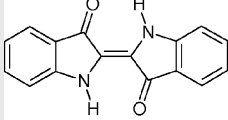
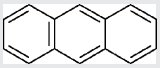
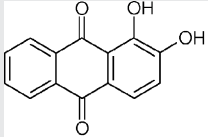
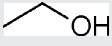





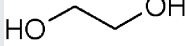
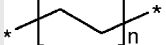


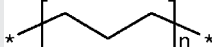

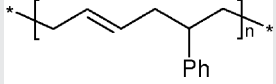
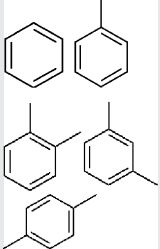
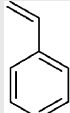
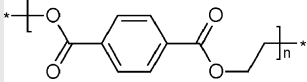
##### 4.3. 1921–1934: pre-development of aliphatic chemicals

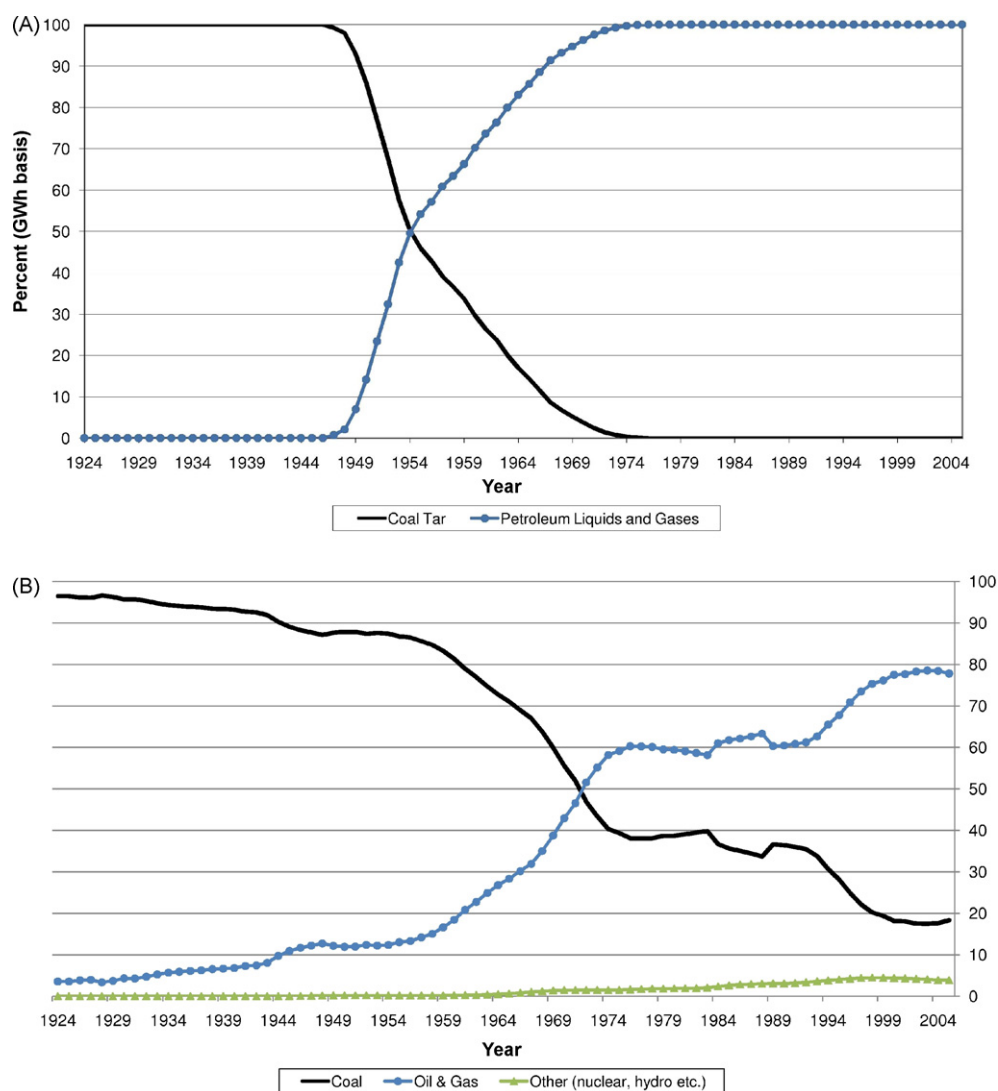
Following WWI it was apparent that the British organic chemical industry was in trouble. Competition from overseas, especially from Germany, had far surpassed the UK's early lead in dyestuffs. From 1921 the government addressed this with import tariffs on dyestuffs (Table 2). The government also subsidised whisky distillers to make industrial alcohol for chemical uses; the distillers faced a growing temperance movement, which was threatening their sales.

Fig. 3 uses causal loops to show the intentions behind the 1921 Dyestuffs Act. The outcomes appear not to have been as anticipated and some were counter-productive. The Dyestuffs Act targeted volume and acted primarily upon the bulk products in which margins were tight. By shielding the partially nationalised British Dyestuffs Corporation (BDC) from overseas competition in staple dyes, however, it did not encourage innovation in the new products that were driving profitable new business overseas. The provision of cheaper alcohol solvents also reduced the pressure of price rises caused by

<sup>2</sup> Section 7, at the end of the paper, provides further notes on nomenclature.

**Table 1 – Groups of platform chemicals and their products in the periods of the transition.**

Primary Raw Material	Platform Chemical	Formula	Industrial/ Historical name	IUPAC name	Exemplar bulk products
Coal (pre-1950)		$C_6H_6$	Benzene	Benzene	 Phenol
		$C_{10}H_8$	Naphthalene	Naphthalene	 Indigo
		$C_{14}H_{10}$	Anthracene	Anthracene	 Alizarin
Sugar (1921–1950)		$C_2H_5OH$	Alcohol	Ethanol	 Ethylene; Alcohol solvents
		$C_3H_6O$	Acetone	Propan-2-one	Nitrocellulose explosives (e.g. cordite)
		$C_4H_8OH$	n-Butanol	Butan-1-ol	Alcohol solvent
Oil and gas (1950 onwards)		$C_2H_4$	Ethylene	Ethene	 Ethanol;  Ethylene Glycol;  Polyethylene
		$C_3H_6$	Propylene	Propene	 Isopropanol;  Polypropylene
		$C_4H_6$	Butadiene	1,3-Butadiene	 Synthetic Rubber
		$C_6H_6$ , $C_7H_8$ , $C_8H_{10}$	BTX (benzene, toluene, ortho/meta/para xylene)	Benzene, methyl-benzene, 1,2-/1,3-/1,4-dimethyl-benzene	 Styrene  Polyethylene Terephthalate (PET)



**Fig. 2 – Transitions from coal to oil and gas in UK primary energy (bottom) and chemical feedstocks (top) 1924–2005 (5-year rolling averages) (Department of Energy, 1975–1992; DoE, 1975; DTI, 1972–1974, 1993–2006; Ministry of Fuel and Power, 1944–1961; Ministry of Power, 1962–1968). Non-fossil feedstocks are excluded from this diagram due to a lack of reliable data. They are thought to account for a shrinking proportion from a high of up to 15% in the 1930s to less than 3% today**

prohibition of imports of cheaper staple dyes, again reducing the need for new, modern processes.

William Pope in his 1918 Presidential Address to the Chemical Society, said that “the scheme adopted by the Government for resuscitating [the coal-tar chemical industry], after its past thirty years of profligate productivity on the Continent, was

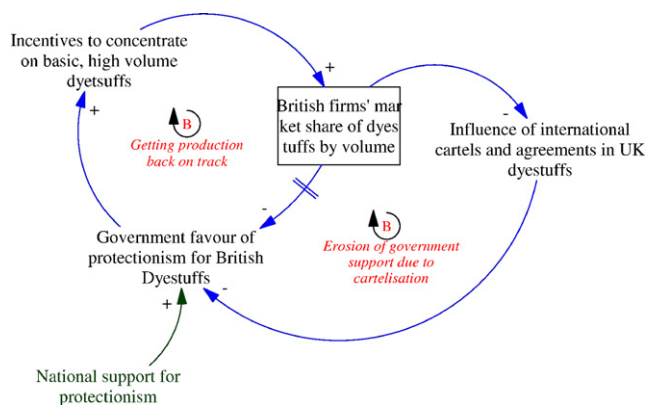
launched without scientific advice” (Pope, 1918). Innovation, he asserted, had been neglected in pursuit of a quick fix. Fig. 4 presents a representation of the difficulties of retaining market share by value.

Fig. 4 shows how the incentives to concentrate on bulk dyestuffs could have retarded the search for new organic

**Table 2 – UK policy interventions in organic chemicals and liquid fuels 1921–1934.**

Year	Policy	Summary
1920–1931	Import Duty on Industrial Alcohol	British alcohol exempted from duty, 5 pence per gallon for Empire alcohol (40% of prevailing price), <sup>a</sup> 35 pence (290%) for foreign alcohol
1921–1939	Dyestuffs (Import Regulation) Act	Only if UK supply was not equivalent to foreign alternatives could imports be authorised by Board of Trade
1921–1945	Inconvenience Allowance	3 pence (25%) subsidy per proof gallon. Compensation for disruptive supervision by excise authorities, and to restrict costs of chemical products. Increased to 5 pence (40%) by end of year
1926	Beet Sugar Subsidy Act	Provides a modest supply of British sugar for power alcohol
1926	ICI Established	Government-sanctioned merger of Brunner, Mond, Nobel, United Alkali and BDC
1928	Acetone Excise Duty	Government assures DCL it will put import duty on acetone, but only if they build a plant big enough for future war needs

<sup>a</sup> Values in parentheses are determined from a prevailing industrial alcohol price of 12 pence per proof gallon reported by Weir (1989), equivalent to £1.79 in 2006 prices as calculated using GDP deflation (Officer, 2008).

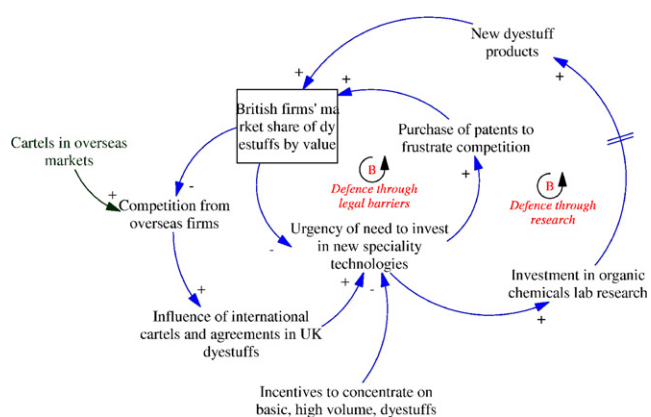


**Fig. 3 – Feedback system representing the intention of the 1921 Dyestuffs Act.**

chemicals. BDC employed a strategy of ‘defence through legal barriers’ to a large extent, and bought their way out of trouble by purchasing British patents for new dyes and engaging in market-sharing arrangements. But they lacked the capital resources necessary to challenge continental firms in the market for the new, higher-value products that continued to be imported in the absence of competing British suppliers. The situation changed when BDC took part in the merger that led to Imperial Chemical Industries (ICI).

ICI was formed in 1926, with BDC as a much weaker partner to the large inorganic-based firms of Brunner, Mond & Co. Ltd. & Nobel Industries Ltd. Government consent for the merger was easily found, as by now effective competition with nationalised German combine IG Farben was seen as essential to the future of chemical manufacture in Britain. It was only through ICI’s substantial capital resources that sufficient money was available to employ the more far-sighted ‘defence through research’ strategy for organic chemistry in the 1930s. Chandler (1990, p. 364) quotes one senior ICI manager, who later said ‘the IG never took much notice of BDC until they found out that BDC could invent.’

The strength of protectionist policies, such as the ‘Inconvenience Allowance’ (Table 2) also created unexpected new directions for distillers (Reader, 1975, p. 322). Against the backdrop of the Import Duty on Industrial alcohol, by the mid-1920s for some industrial applications domestically produced alcohol was recognised as a potentially cheaper feedstock even than coal or oil. For the largest consolidated alcohol producer, DCL, this meant first taking on gasoline and then organic chemicals.



**Fig. 4 – Feedback structure of the British dyestuffs market in the 1920s.**

Although UK gasoline consumption lagged far behind that in the US, concerns over import-dependence ran higher due to the perceived lack of home control over supply. There was a deep suspicion of the foreign oil majors, after Standard Oil was accused of market manipulation in the US, and British interests in Royal Dutch Shell had failed to persuade the government that the firm’s aggressive approach did not constitute a ‘Shell Menace’ (Jones, 1981, p. 150).

Private consumers and societal actors were uncertain about the displacement of coal and the potential of new oil-consuming technologies. Thus, a century ago, there were already concerns about energy security and actions in restraint of trade and proposals for the substitution of petroleum by alcohol-based fuels: in 1912 the UK magazine *Engineering* argued that the prospects for oil engines were inhibited by the fear that prices would rise. It wrote that ‘This fear is based not so much upon any likelihood of demand overtaking supply as upon the supply being in the hands of a comparatively few large companies who may manipulate the markets’ (Jones, 1981, p. 43). Both the *Daily Mail* and the *Times* discussed the ‘petroleum problem’ in 1913 and cartoons were published that showed motor vehicles exhausted and then revived by whisky (Weir, 1995, p. 291). This reflected the popular view that domestic-alcohol could be used instead of oil in cars, evidenced in a 1915 *New York Times* report of ‘agitation’ for alcohol fuels by English farmers (Bernton et al., 1982, p. 9).

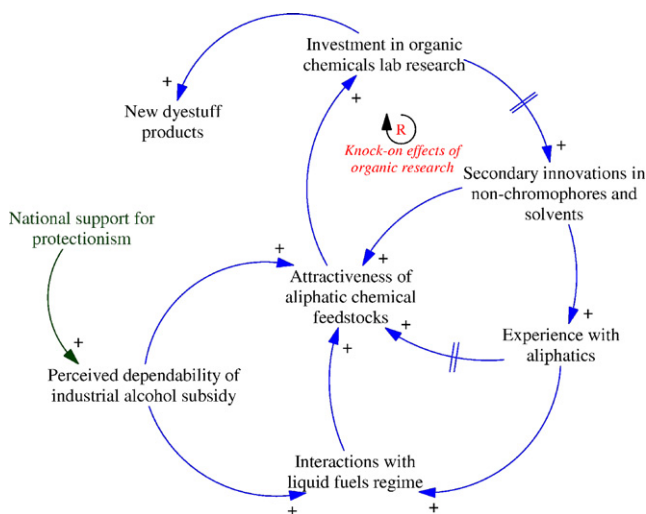
When the Inconvenience Allowance was introduced in 1921, DCL were in a position to exploit the demand for home-produced motor fuels. No other country provided a subsidy similar in size or scale. The subsidy was not just available to the struggling cereal-using whisky producers but also for raw materials imported from the Empire and refined in the UK. This gave the import of molasses, a by-product of Caribbean sugar production, a distinct advantage through economies of scale and ease of fermentation (Weir, 1995, p. 296).

In 1921 DCL began marketing Discol, a gasoline–ethanol blend. Shortly afterwards the supply was based on a new molasses facility rather than using the existing potable alcohol capacity that the Inconvenience Allowance had been designed to assist. Discol’s market penetration suffered technically from difficulties with the separation of the fermentation water from the fuel blend, although the blending of pure ethanol yielded a cheaper and better fuel than straight-run gasoline. Although DCL successfully supplied fuel to race-cars to demonstrate the superiority of Discol in high performance engines (Weir, 1995, p. 299),<sup>3</sup> phase separation problems experienced by private motorists outweighed this positive publicity. Its market was also damaged by a sharp drop in the oil price, which Weir (1995, p. 295) has ascribed to collusive oil company strategy in response to the competition from Discol.

Ultimately, the failure of alcohol seriously to challenge gasoline led DCL to develop derivatives of the ethanol solvents they were selling cheaply to chemical manufacturers. These derivatives included higher value chemicals such as ethylene glycol antifreeze. Ethylene glycol was at that time imported from Union Carbide, who used the by-product gases of US oil refineries. This oil route was not a serious UK option, as Iranian

<sup>3</sup> A publicity strategy also employed 10 years later by AIOC upon the introduction of tetraethyl lead (Bamberg, 1994, p. 196).





**Fig. 5 – Positive feedbacks led from dyestuffs research to new aliphatic products.**

policy demanded that AIOC<sup>4</sup> (the forerunner of BP) undertake baseload refining of the principal British oil reserves *in situ*. This left alcohol as a cheap and reliable feedstock for the new aliphatic chemical products in Britain. DCL Chairman, Ross, wrote in the DCL Gazette in 1929, that the distilling industry would leave the ‘whisky age’ and enter the ‘alcohol age’, by ‘producing alcohol and co-relative substances’ for an expanding chemical industry (Weir, 1995, p. 285).

The major oil companies, moreover, were not yet interested in chemical production. Distillation of gasoline remained a comparatively crude technology: this ‘up to the 1920s, very little technological contact had been established between the petroleum and chemical industries. The former were oriented towards fuel and lubricants, the latter towards chemicals and the use of coke-oven by-products as primary feedstocks’ (Spitz, 1988, p. 76). By the late 1920s DCL’s activities in fuel and chemicals bridged the industries, creating links between the regimes through niche innovations in ethanol upgrading (Fig. 5).

ICI did not follow DCL into aliphatics, due to their corporate dependence on coal. The company had located near the Durham coalfields to pursue a different technological pathway: high pressure hydrogenation of coal to oil, and fertilisers. These plants were similar in scale and ambition to ICI’s existing large alkali plants. ICI also had a knowledge sharing arrangement with DuPont, who were keen to tell them that in coal-based synthesis gas they had ‘an answer to anything the oil companies can do from hydrocarbon gases’. ‘A long distance policy based on coal’, DuPont later told ICI, ‘is sounder than one based on oil as there are periodic doubts whether the oil resources have anything but a limited life’ (Reader, 1975, p. 321). From the outset, ICI’s business was driven by Chairman Alfred Mond’s belief that ‘not only oil, but the whole field of organic products will be based upon coal as a raw material in the near future’ (Reader, 1975, p. 84). ICI were aware of the likely public approval of a large-scale coal-to-oil project. Small volumes of coal-derived liquids obtained from coke oven by-products had been blended with petrol to reduce knocking and

marketed as a patriotic choice for some years (Flight, 1929). As the prominent British coal industry suffered the effects of fuel oil imports and recession, the progress of ICI’s hydrogenation technology became the subject of parliamentary questions, a matter that was assisted by the company chairman sitting in both houses of parliament during this phase (HC Deb, 1928).

By 1934, although there had been no wholesale change in products and feedstocks in the UK liquid fuels and organic chemicals regimes, the foundations had become unstable. New feedstocks, alcohol and petroleum, had appeared but politicians and the media alike had shown distrust rather than support for the oil industry, which was trying to grow the European liquid fuels market. For coal-to-oil, after the 1929 agricultural depression had destroyed fertiliser demand (Madsen, 2001), ICI disclosed that public money would be needed to make coal hydrogenation a reality. It was hard to see which feedstock would prevail, with decisions being dictated by companies’ internal experience and political intervention rather than a firm belief in long-term commercial sustainability.

#### 4.4. 1934–1945: technical specialisation in both regimes—overlapping know-how in aliphatic chemicals

The pre-WWII period was characterised by a continuing uncertainty over feedstock sources and little coherence in government support, which variously supported coal, oil and alcohol (Table 3). This led to moves either to hedge bets by entering corporate agreements, or to attempt to ringfence markets through lobbying. Two areas appear to have been particularly notable: polymers/plastics, and high octane aviation fuel. We concentrate here on the ‘race’ for better aviation fuel that occurred in the run up to the war. While it was not more significant than the role played by breakthroughs in polymer science, we have chosen to focus on the events that led to a union of the two regimes—a more complete account will be made available elsewhere (Bennett, forthcoming).

In 1934 ICI had finally succeeded in securing the British Hydrocarbon Oils Production Act, which guaranteed a preference of 8 pence per gallon for 4.5 years in favour of petrol produced in the UK from British coal (Reader, 1975, p. 129). This kept alive the coal-to-oil project at Billingham and kept the coal option open for bulk organic chemicals. The Act also included alcohol-gasoline blends and so the distillers remained competitive in fuels wherever they were able to evade the local distribution monopolies of the oil majors.

If the long-term raw material choice for fuel was not clear, there was also no obvious winner between the three main choices for organic chemicals. Alliances were formed and broken to delay firm commitments. DCL allied themselves first with ICI for exchanges of ethanol hydration products, then from 1937 with US firm Union Carbide to access petroleum and synthetic alcohol knowledge. Talks with Union Carbide about petrochemicals collapsed, however, as DCL were unprepared to abandon fermentation alcohol as their basic feedstock (Weir, 1995, p. 357). A similar fate then befell Standard Oil in their attempts at a joint venture based on DCL’s alcohol-derivatives business in 1938. DCL were only willing to use alcohol in the first instance; later they came to consider petroleum and possibly coal (Weir, 1995, p. 329).

ICI and AIOC collaborated on cracker gases from AIOC’s Iranian refinery, but in 1939 ICI’s Development Department, under pressure from their agreement with DuPont, stated that

<sup>4</sup> Anglo-Iranian Oil Company. The firm was incorporated in 1909 as the Anglo-Persian Oil Company and the name changed to AIOC in 1935. In this paper we refer simply to AIOC during the entire pre-BP period to limit confusion between acronyms.

**Table 3 – UK policy interventions impacting organic chemicals and liquid fuels in the second phase (1934–1945).**

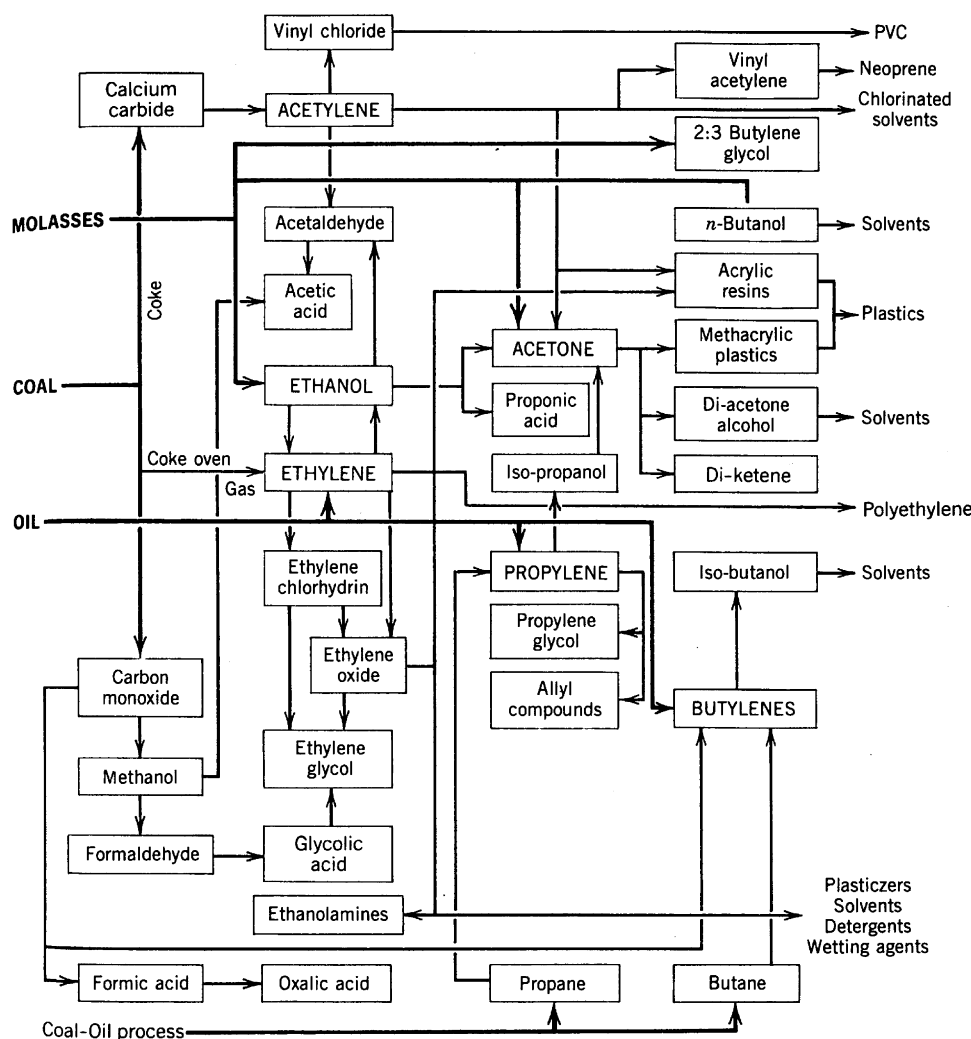
Year	Policy	Summary
1931	Alcohol Import Duty Removed	Import duty lifted, which helps power alcohol
1934–1939	Hydrocarbon Oils Production Act	8 pence per gallon subsidy for UK coal-based gasoline, and alcohol-gasoline blends, incl. from imported molasses (>50% of after-tax price)
1937	Falmouth Committee	Concludes that coal-to-oil could not be justified, but subsidies should continue to encourage Fischer Tropsch technologies
1937	Alcohol Import Duty Reinstated	4.4 m gallons per year had been blended with gasoline (0.5% of total UK demand for gasoline)
1938	Imperial Defence Committee	Report recommends keeping seas clear for imports of oil rather than use coal-to-oil
1938	Hydrocarbon Oils Production Act Amended	Subsidy removed from alcohol from imported molasses
1939	Octane Standards	100 octane for RAF fuel introduced
1939	Petroleum Board Agreement	Wartime gasoline infrastructure and fuel pooled

‘fundamentally, coal is our ultimate raw material and failing oil refinery gases we should aim to base all our organic manufactures on it’. They had struck an agreement in 1931 with IG Farben and Standard Oil to share coal and heavy oil hydrogenation expertise, but no agreement about petrochemicals was reached with the oil majors (Reader, 1975, p. 168). This was primarily because ICI’s historic self-sufficiency in raw materials made them averse to such joint ventures. In turn the oil companies were not interested in selling their by-product olefins cheaply; they wanted to integrate downstream to enjoy the values that Shell and Standard Oil had begun to demonstrate in the US. In 1944, ICI was equally committed to each

of industrial alcohol, coal and oil (Fig. 6) (Reader, 1975, p. 320; Spitz, 1988).

**4.5. The aircraft octane race**

From our study of the contemporary events it can be surmised that the involvement of ICI, Shell and AIOC, in the so-called ‘octane race’ (Sinclair Oil Corporation, 2007) played an important role in uniting the two regimes around petroleum feedstocks. Although ICI’s coal-based gasoline was of sufficiently uniform quality for aircraft compared to straight-run petroleum gasoline, it became clear in the mid-1930s that



**Fig. 6 – ICI’s organic chemical process streams in 1944.**

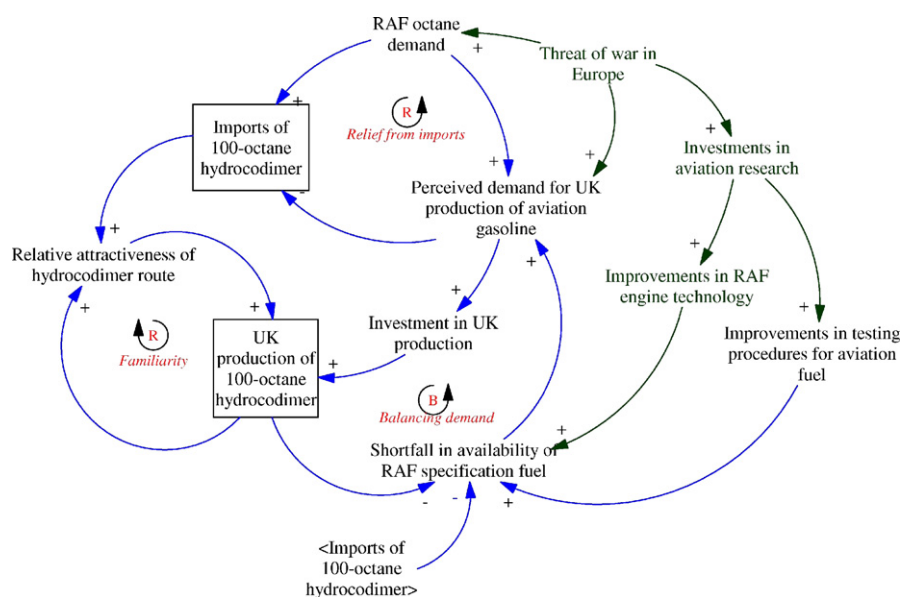


Fig. 7 – The web of factors that led to the UK pursuit of hydrocodimer aviation fuel in the late 1930s.

the potential demand from the new fleets of Royal Air Force warplanes would overwhelm supply. However, an important by-product of ICI's experience with coal was that the UK had indigenous expertise in a technique that could produce high quality aviation fuel.

In 1937 in the US Standard Oil and Shell produced the first 100 octane blend, by using a butane dimer hydrogenation process originally developed by IG Farben and ICI for coal. It can be surmised that this technology gained favour and momentum as war approached, because of aircraft developers' familiarity with this products. Initially, imports could balance shortfalls in availability, but improvements in engine technology and testing raised fuel specifications above US standards, creating further shortfall. These positive feedbacks are shown in Fig. 7. In 1937 the Air Ministry contracted ICI and Shell to produce hydrocodimer fuel in the UK (Bamberg, 1994, p. 199).

AIOC were excluded despite their ongoing research into a novel method of alkylating a butene–butane heterodimer (diiso-butene) to improve the octane of Iranian gasoline. They were at the pilot stage by 1939 (Bamberg, 1994, p. 203).

It was only the massive levels of demand created from 1939 by WWII that pushed AIOC to continue work on 'cold acid alkylation', despite their having initially lost out to the hydrocodimer route. Eventually, their technology proved that alkylation was the more effective route and, employed in Iran, AIOC exceeded the production of all 100-octane from all other British plants (Bamberg, 1994, p. 245). Fig. 8 proposes a reinforcing feedback that allowed investment to flow towards

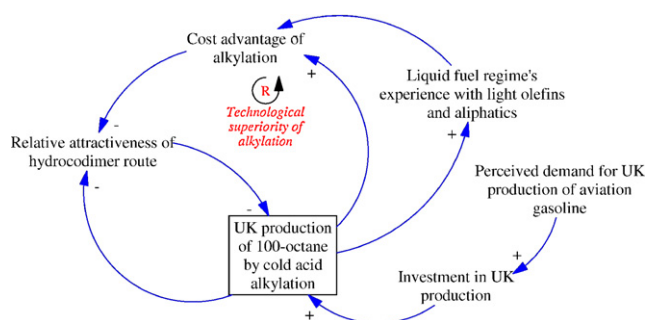


Fig. 8 – Causal loops representing the rise of alkylation for aviation fuel.

AIOC's alkylation process as its cost advantage became evident. Without heavy pressure from the demand for wartime aviation fuel, it seems unlikely that such a feedback could have so rapidly overcome the established 'attractiveness' and support for hydrocodimer.

#### 4.6. 1945–1967: wide diffusion—the switch to home refining and regime convergence

The legacy of WWII in the two regimes was a cross-fertilisation of knowledge on production of chemically superior fuels from oil, and an appreciation of the potential of polymers such as PVC, nylon, and polyethylene. The economics of the Inconvenience Allowance had dictated that ICI's first polyethylene plant in 1938 was based on fermentation ethanol feedstock, purchased from DCL. The Inconvenience Allowance was removed in 1945 (Table 4).

The subsequent removal of import duty on petroleum imported for chemical manufacture significantly altered the rules of the game for the companies in the regimes. For DCL and ICI the question now was whether to become reliant on the oil companies for feedstock, or to develop their own oil supplies. For the oil companies it was a matter of whether to refine in the UK, or to stay near the wellhead and export products to Britain.

DCL were concerned that their solvents trade would be imperilled 'as the oil people would be able to cut prices of these as by-products' (Weir, 1995, p. 329). This concern was supported by their dealings with Standard Oil in 1938 about entry to the UK alcohol market. Standard's Frank Howard had told DCL that if oil was to replace molasses in industrial alcohol, then the oil companies should produce it, unless DCL had a better cracking technique than they did (Weir, 1995, p. 329).

Whilst DCL fretted about competing with the oil companies, ICI were concerned about a potential dependence on them. They reported in 1944 that 'on the information immediately available within ICI, it is unsafe to make a clear cut recommendation between the oil route and the molasses route [to ethylene] since the cost of raw material is so important and so dependent on external factors in the arbitrary control of other companies' (Reader, 1975, p. 396). Not moving towards oil was also a risk. ICI's Dyestuffs division concluded

**Table 4 – UK policy interventions in organic chemicals and liquid fuels 1945–1967.**

Year	Policy	Summary
1945	Inconvenience Allowance Abolished	Government acted on evidence of monopolistic behaviour by DCL reported by the May Committee
1945	Distribution of Industry Act	Development Areas defined to attract investment. ICI lobby to get controversial public grants for Wilton
1946	Coal to oil conversion programme	Coal shortages prompt government to promote switching to fuel oil
1946	Finance Act	Hydrocarbon oils for chemical manufacture exempted from import duties
1947	Finance Act	Light hydrocarbon oils for chemical manufacture exempted from all oils taxes
1953	Petroleum Board Agreement rescinded	'Pool' gasoline removed, oil companies can differentiate sales of varying octane fuels to motorists
1961	Finance Act	Double Taxation Relief provided for UK downstream activities if upstream operations were taxed abroad

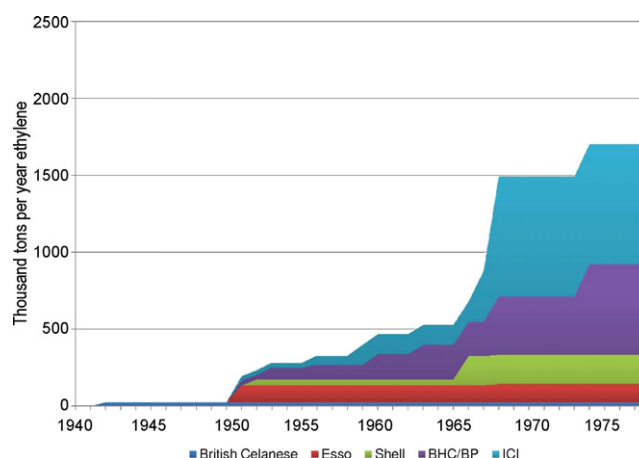
that 'in the event of ICI taking no definite action the control of the aliphatic field will pass into the hands of others, which may well prove a crippling handicap' (Reader, 1975, p. 395).

For AIOC there had been little previous incentive to enter UK petrochemicals. They could ship refinery products globally from an Iranian refinery and had positioned themselves firmly upstream. Olefins had traditionally been flared; they could not then be transported abroad, and Iran had no industry to use them. Experience with new chemical technology in the production of wartime aviation fuel had demonstrated the potential value of olefins in synthetic products but AIOC had few operations on British soil and no access to chemical markets.

Two additional technological and landscape changes can be identified as persuading AIOC to move to UK refining. Firstly, rapid increases in ship sizes made the competitive shipment of liquid products from Iran to each small European port less attractive. Large shipments of crude to be refined and piped within each country suddenly became a cheaper alternative (Bamberg, 1994, p. 291). Secondly, the political security of their operations in Iran was threatened, affecting the requirement for Iranian refining of Iranian oil.

AIOC's strategy for moving into petrochemicals, therefore, was to partner a chemical firm. Although ICI was their first choice, ICI wished to be independent in raw materials and insisted on locating activities at Wilton, near Billingham. ICI were naturally mistrustful of surrendering control for any part of what they considered to be their value chain (feedstock to bulk unfinished product). They were also committed because of a political agreement that the South of the Tees would be included in the post-war North East Development Area and they could receive government assistance with investment and planning permission at Wilton (Pimlott, 1986, p. 624). By working with US engineering firm Kelloggs on a novel steam cracking pilot, ICI confirmed the feasibility of importing naphtha, a better feedstock than regular crude or gas oil commodities (Obuasi, 1986). Scale-up would entail building the world's first petrochemical plant independent of the fuels industry, at the edge of technological viability. Although it meant employing foreign consultants to fill gaps in petroleum knowledge, in every other way it resembled the previous coal-to-oil and nitrogen fixation projects in terms of scale and independence.

DCL, on the other hand, were relative newcomers to chemicals—and on the back of a subsidy that had since been removed. Although they had much of the knowledge and associations necessary for aliphatics, chemicals remained the smaller of DCL's alcohol-based operations. Weir (1989) noted that DCL management continued to consider chemicals to be



**Fig. 9 – UK Catalytic Cracker Capacity Additions (using data from the events database). N.B. – decommissioning not included.**

'but an insurance policy until the potable industry recovered'. The fit between DCL (downstream) and AIOC (upstream) led to a marriage of convenience in the form of British Hydrocarbon Chemicals (BHC)<sup>5</sup> that would pool chemical competences, except for DCL's solvents, including ethanol, and AIOC's fuels businesses. The new alliance centred on AIOC's plan for a catalytic cracker at their existing Grangemouth refinery.

Until WWII Shell had comparatively little infrastructure in Britain, although it had a gasoline refinery in the Thames Estuary and had arguably produced Europe's first petrochemical, a small-scale detergent, on Merseyside in 1942. Involvement in the wartime aviation fuel projects put Shell in a position to benefit from the UK becoming the centre of European chemicals investment under the post-War Marshall Plan (Stokes, 1994). Shell purchased Petrochemicals Ltd., which operated Catrole refining in Manchester (Tugendhat, 1964). This secured them a low-risk entry into bulk olefins, and the possibility of linking to Stanlow nearby, where they invested in solvent production.

Including the investment by Exxon<sup>6</sup> in their existing gasoline facilities on the South Coast, four parallel projects were undertaken for the catalytic cracking of distillation products to high quality gasoline. Fig. 9 shows that the competition between firms to erect new crackers led to all four sites coming online in the first years of the 1950s, as financing constraints were lifted. The figure shows that despite a strong industrial

<sup>5</sup> Initially called British Petroleum Chemicals.

<sup>6</sup> A successor of Standard Oil.



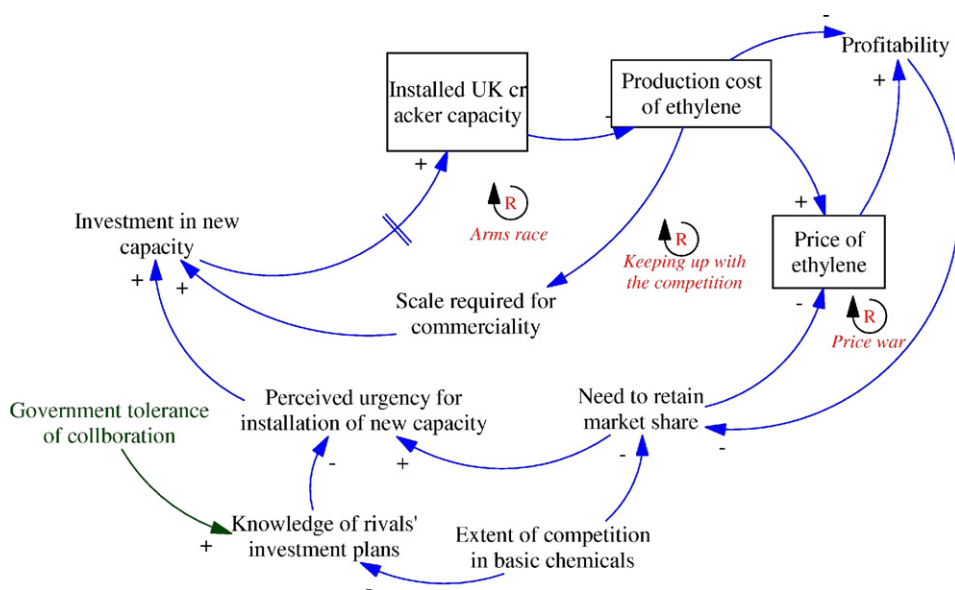


Fig. 11 – Dynamics of competition in new cracker capacity 1945–1975.

benzene from coal was still more than half (147 million gallons) of a total chemical demand (258 million gallons) (Spitz, 1988, p. 184). A final phase, involving a slowdown of capacity additions and new products up to the 1979 oil crisis, has not been covered here as the transition can be considered complete by 1967 when BP bought out DCL from BHC and moved firmly downstream to become the nation's second largest chemicals firm. Only one new world-scale cracker has been built in the UK since this development, and this was a joint project between ICI and BP.

#### 4.7. Conclusions and insights from the historical study

Several important results emerge from this structured analysis of the historical development of petrochemicals in the UK between 1921 and 1967. They are interpreted below, in accordance with the framework of the MLP.

1. Change can be effected by destabilising influences at different levels of the system: feedstock change began in the UK in the 1920s as a result of a disruption of the relatively stable existing regimes. This disruption emerged mainly at the landscape level, with public concern regarding reliance on foreign imports of fuel and developments in aliphatic chemistry in the US and Germany, as well as a regime-level crisis in the distilling industry.
2. The transition in the UK did not occur quickly or smoothly, even though the benefits of using light petroleum gases as chemical feedstocks had been well demonstrated in the US by the end of the 1920s. Landscape pressures, such as suburbanisation, that drove gasoline demand in the US, were important but less strong in the UK, where energy security related positively to domestically produced coal and alcohol, but not oil.
3. Political measures applied directly to the two regimes, i.e. Organic Chemical Production and Liquid Fuels Production, strongly directed technological change, as did the knock-on effects of policies in other sectors (e.g. alcohol distilling). Innovation was steered in the direction of coal and industrial ethanol during the 1920s and 1930s, under the guidance of subsidies for fuel and alcohol.

4. There was little interaction between the two regimes in the UK during the first two phases, except under the landscape pressures of war. Both WWI and WWII acted to induce cooperation between the regimes to accelerate innovation and change.
5. There is clear evidence of technological 'lock in' and resistance to change: innovations in petroleum technology that arose on the edge of the system in the US were unable to diffuse into the UK organic chemical regime, due to the tight networks of interests that supported the routines of existing feedstock use. A clear example is the unsuccessful attempts by Union Carbide in the late 1930s to introduce synthetic ethanol, which was one of the first products to be produced after the war, when the 'rules of the game' were changed.
6. Petrochemical complexes were not built immediately as fully integrated plants even though there had been two decades of prior experience overseas. Integration evolved through a process of clustering of downstream operations around a feedstock source and emergence of a new search heuristic oriented towards olefinic platform chemicals.
7. Co-evolution of the two regimes seemed to be a dominant dynamic: changes in the selection environment in one regime affected the selection environment in the other.
8. The agency of actors in the system was significant: corporate managers chose different strategies that were not based solely on economic efficiency and depended on the perspective of their firm's role in the market. Examples include DCL's consideration of industrial alcohol as a secondary business to potable uses, AIOC's adherence to a position as an upstream supplier of unprocessed products and ICI's commitment to independence from the oil majors. ICI's position became untenable by 1967, when they partnered first Phillips Petroleum, then BP, in fuel refinery projects in the North East.

#### 5. Discussion of the implications for biorefineries

These findings offer insights into whether and how new feedstocks might begin to displace petrochemicals.

**Table 6 – 3 Stylized biorefining models with different levels of spatial integration.**

Biorefining model	Spatial integration	Process integration	UK petrochemical example
Complex	High (one large site)	Fully integrated through services and by-products, producing fuels, polymers, bulk and specialty chemicals	Shell Carrington & Stanlow
Clustering	Intermediate (regional clustering of downstream users around a pre-treatment facility)	Centralised pre-treatment allows smaller users to enter and exit the cluster to use the available output	BHC's sites at Baglan Bay and Grangemouth resembled this to some extent
Distributed Hubs	Low (initial processing to fungible commodities separate from distributed users)	Some integration of services and by-products downstream, possibly hybridised with petrochemicals	ICI shipped in pre-distilled naphtha to Wilton, whilst other oil fractions went to fuel refiners (e.g. Exxon)

### 5.1. Co-evolution

Advocates of biorefineries might be wise to acknowledge the established links between fuel and bulk chemical production and to consider how these regimes might now co-evolve, or whether, to what extent and why the link might become broken. It is not pre-determined that a biofuels industry necessitates a co-dependent bio-chemicals industry, but the ability to hedge against different markets and integrate vertically has contributed to the success of petrochemicals firms. The cross-fertilisation of technologies between the two regimes and the potential economies of scale were important catalysts for the establishment and continued development of petrochemical sites in the UK. From this perspective, the massive disparity in the size of markets for fuels and chemicals in terms of volume provides an advantage to firms already situated in fuels production. Hence, we may see some oil firms return to chemical co-products as a diversification strategy in a new, and thus higher-risk, biorefining industry, just as they did with petrochemicals in the UK in the 1950s.

On the other hand, the oft-cited analogy between biomass and oil refining is questionable. The fractions derived from oil distillation and cracking are dissimilar and suited differentially to the production of gasoline, diesel, turbine fuel or olefins. The initial processing steps for bio-derived oils and plants produce fractions, such as cellulose or syngas, which represent feedstocks for both fuels and biochemicals. There is, therefore, a direct competition between these uses for the biomass resource, which may itself be more limited and less fungible than annual petroleum production has been. The strategies of ICI (after the demise of coal-to-oil) and Exxon enshrined the separation of fuels and chemicals until the mid-1060s; both constructed petroleum-using sites with little on-site interaction between the regimes.

Biomass may be a different prospect to petroleum but there is nevertheless a relevant message from the co-evolutionary history of petrochemicals. Output and technological development soared after the two regimes had become more closely aligned, but this occurred after the foundations had been laid independently in each sector. The technologies for producing the major products of the subsequent petrochemical revolution (e.g. high octane fuel, polyethylene, PVC and nylon) were developed before 1950 using coal, alcohol and furfural.<sup>8</sup> Changing the feedstock at this stage provided a competitive

strength and greater scalability. Yet aiming for integration in petrochemicals earlier would have been a complex strategy with the associated risks of developing several new markets and processes concurrently.

If integrated biorefining is a long-term goal then its achievement may be advanced by supporting the independent development of bio-based products and processes in the near-term. Integration will emerge and will drive change if benefits to continued regime-regime co-evolution become apparent, for example through valorisation of by-products or a shared pre-treatment stage. Biorefining for chemical products on standalone chemical sites should, therefore, be incorporated into our visions of the future, as should standalone biofuels sites. This is clearly reflected today in the parallel development of the European biofuels and bioplastics industries with separate institutions and visions of biorefineries (Bennett, forthcoming).

### 5.2. Spatial path dependence

This analysis of the transition to petrochemicals in the UK indicates that the technological pathways followed in a given region are likely to relate closely to the existing industrial competences and infrastructures. There may be obvious advantages to siting a biorefinery close to feedstock, but early biofuel and bio-based chemical developments in the UK have mainly occurred close to the existing industrial infrastructure and expertise. This reflects the persistence of the North East of England as a centre for chemical manufacture since its founding close to a source of coal. Other candidates for biorefining in the UK could include existing inland starch mills, pulp and paper mills, and coastal petrochemical sites that could import biomass.<sup>9</sup>

In order to avoid the transport of large amounts of wet feedstock, it could be advantageous to conduct the initial processing of biomass close to the point of harvest. Reconciling this with the advantages of locating close to existing infrastructure and markets could give rise to new biorefining models. One can envisage stylised models with different levels of spatial integration (Table 6).

The concept of spatial path dependence makes it apparent that future biorefinery designs may vary tremendously depending on existing infrastructure and supply chains. This is likely to be compounded by regional variations in raw materials. The message from this historical work is that the

<sup>8</sup> an aromatic industrial chemical derived from agricultural crops such as wheat bran and used as a solvent in petrochemical refining as well as an in chemical products.

<sup>9</sup> see Reineck (2008) and Black and Veatch (2008) for a discussion of location issues in the UK.

integration of biorefining is part of an ongoing evolutionary process shaped by the past and by policy. Petrochemical refining in the UK resulted from a sharp change to the policies in the two regimes and became shaped by the incumbent assets of the sectors. Integration of processes was the result rather than the objective. Likewise, a departure from centralised chemical processing and global trade in feedstocks indicates a strong role for climate and rural development policy as well as support for industrial regeneration.

### 5.3. Strategic alliances

Disruption of the existing regime by landscape pressures provides an opportunity for existing actors and outsiders to enter new areas of the socio-technical system. In the 1920s disruption was caused by new policies in the associated potable alcohol sector, growing social and political demand for liquid fuels and political responses to cartelisation in industry. In the current climate we are witnessing disruption to the established routines in petrochemical production. Environmental concerns are causing a rethinking of products and feedstocks with regard to Greenhouse gases (GHG), toxicity and end-of-life degradation (Jenck et al., 2004). Security of resource supply concerns and volatile petroleum prices are prompting research into alternative feedstocks (Diercks et al., 2008; Tremblay, 2007; Van Haveren et al., 2008). Agricultural reforms in Europe and overseas are providing incentives for non-food uses of agricultural land (Bos et al., 2008). As a result, ‘outsiders’, such as agricultural and food producers, are well placed to enter the new industry on the basis of experience in handling the new feedstocks but, like DCL, they may find stiff opposition from incumbent firms.

DCL, ICI and AIOC found entry into the bulk petrochemicals sector through partnerships. During the uncertainty of the 1930s/1940s a number of such dialogues were initiated between regime insiders and outsiders: between chemical and bulk carbohydrate firms (ICI and DCL), fuel and chemical firms (ICI and AIOC, DCL and AIOC, DCL and Union Carbide, DCL and Exxon), fuel and process engineering firms (AIOC and Kelloggs, AIOC and UOP) and chemical and process engineering firms (ICI and Kelloggs). Although the feedstock providers and the manufacturers of downstream chemicals had a clear incentive to discuss partnerships, there was a key role for the process engineering firms (or SEFs<sup>10</sup>). These firms licensed their experience in the early US oil refining business and enabled cross-fertilisation of chemical engineering knowledge between the two regimes and reduced the cost of development.

The message for biorefining is not simply that we can expect new entrants into the existing regimes, but that facilitating knowledge transfer between the different levels of the regime may be of vital importance. The value of partnerships is indicated in the area of ‘white-biotechnology’ where recent major partnerships have covered: chemicals plus bulk carbohydrates (DuPont and Tate & Lyle, DSM and Roquette); chemicals plus biotechnology (DuPont and Genencor, Goodyear and Genencor); chemicals plus agricultural products (Dow and Cargill, Novamont and Coldiretti, PolyOne and ADM); chemicals plus fuels (DuPont and BP); fuels plus bulk carbohydrates (BP and British Sugar); fuels plus agricultural products (ConocoPhillips and ADM). This list sug-

gests that biotechnology firms may play a similar role to that played by the SEFs in petrochemicals. To enhance integration and hasten the development of sustainable biorefining technologies, governments may seek to facilitate dialogue with biotechnologists, with whom many established chemicals manufacturers have had little interaction.

### 5.4. Dominant designs and platform chemicals

Partnerships, therefore, bring together enabling technologies but also have the potential to establish norms and standards that are transferred via technology licensing. SEFs competed to sell their first crackers to AIOC in the 1920s in order to establish what Anderson and Tushman (1990) have called the ‘dominant designs’, which would become the industry standard. There is also evidence in the historical narrative for dominant designs in the acceptance of platform chemicals. Before WWII the UK firms were not prepared to accept the dominance of olefins and BTX over alcohol and coal-tar benzene. Once the two regimes had aligned around the dominant cracker designs, and a number range of commercial petrochemicals were proven, olefins constituted a new platform of building blocks around which research could be rationalised. The Succinium™ partnership between DSM and Roquette can be interpreted as an attempt to induce a research and investment consensus around a new succinic acid platform; as can endorsements of fuels and chemicals based on furanics or ethanol derivatives.

For the petrochemical industry oil refineries commoditised olefinic platform chemicals and then BTX. Bio-based bulk and specialty chemicals and solvents would all benefit from a similarly reliable supply of chemical building blocks but history suggests that only time will be able to decide which these might be. Biorefinery designers are thus caught between optimising production of products they anticipate will become dominant or retaining the flexibility to wait-and-see. Ethanol appears to be a good candidate to substitute for ethylene but it does not enjoy the same by-product relationship with a bulk fuel. Indeed, competitive production of ethanol (or butanol) may rely on a large-scale fuel demand for alcohols, demanding that other uses outbid the energy value of the molecule. In the longer-term the production of aromatics from by-product lignin offer promise in this respect.

### 5.5. Future research

This work on past transitions is presented here as we believe that an understanding of past dynamics and co-evolutionary processes and the insights described can inform the present discussion on the future of biorefining. We also aim to employ the dynamic hypotheses presented in the figures in foresight applications. The intention is to construct scenarios that build on these dynamics and which identify the feedback systems that could advance or obstruct the technological options for RRM. As an example of the use of causal loops for foresight scenarios, Fig. 12 proposes a situation in which the dynamics underlying change echo those of the 1921–1945 period when developments in fuels drove change in organic chemicals. In this ‘biofuels drive change’ scenario biofuels are the main driver for change and RRM in chemicals are adopted to valorise by-products such as glycerol and highly functional specialties, and to hedge against oil price collapses.

Visual presentation of these dynamics has the potential to highlight points for possible government intervention to assist

<sup>10</sup> Specialised Engineering Firms.



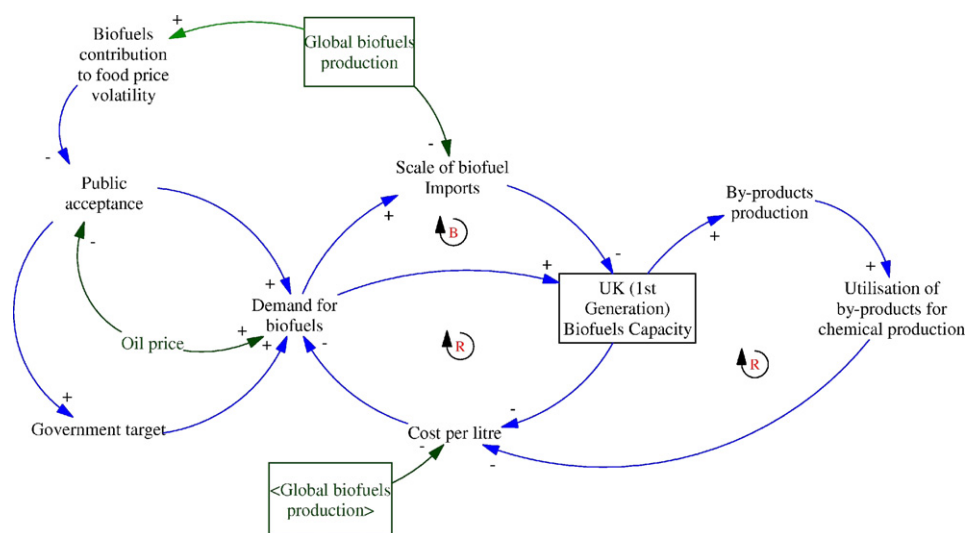


Fig. 12 – Knock-on effects of a successful biofuels support strategy.

attractive future scenarios; for instance by directing sponsored research into new markets for anticipated by-products such as lignin or glycerol. Our research is intended to complement more quantitative work such as that being undertaken in the EU Biopol project, and which suffers from a largely intractable problem of complexity in quantifying future chemical products and markets (see discussions by Bozell, 2008; Chamboost and Stuart, 2007; Patel et al., 2006).

Rather than only questioning the fundamental efficiency of replacing petroleum with RRM in fuel or materials, it is worth asking under what circumstances RRM could realistically break into bulk chemical markets. For instance, does the scale of the potential biofuels market mean that without successful development of second generation biofuels the necessary supply chains, economics and confidence in RRM will remain insufficient?

## 6. Conclusions

This paper aims to make several relevant contributions to the existing literature. In the evolving research area of socio-technical transitions and the multi-level perspective, it expands the literature into the technological field of organic chemicals production, an area that has not previously been studied within this body of work. By including the liquid fuels regime in the study alongside the organic chemicals regime the role of co-evolutionary dynamics between closely interacting sectors has also been incorporated. In addition, a methodology has also been proposed for analysing past transitions in a systematic manner that enables the insights to be transferred into foresight applications such as scenario building and policy recommendations.

It is our hope that the approach taken and the analysis presented in this paper might contribute to the building of a bridge between technical knowledge and political processes and decision making about prospective feedstock transitions. Whilst our analysis and findings relate specifically to the experience of the UK, we suggest that the approach, including the use of the causal loop diagrams, to understanding interactions and dynamic processes within and between the organic chemical production and the liquid fuels production regimes is more widely applicable, and might help to inform and structure the current debate about integrated biorefineries.

This paper suggests that it is time to move beyond designing the ideal biorefinery on paper and to look at how a framework could be established that would allow biorefineries to evolve towards greater efficiency. High levels of integration could be a natural long term outcome of a stable policy regime that encourages sustainable biomass processing, diversity in bio-based consumer products and stability in markets for these products. History informs us that feedstock transitions have not been ‘one-size-fits-all’ processes; different regions and actors react differently to threats, opportunities and policy goals.

The biorefining industry is at a very early stage of development and alliances between sectors are exploratory, yet early developments will shape future pathways. In this paper we have tried to show how socio-technical analyses can yield insights into the dynamics of past feedstock transitions and how they might help to identify potentially important future interactions between co-evolving sectors and between niche innovations, technological regimes and the broader socio-political landscape. We suggest that these dynamics could have significant influences on whether biorefineries emerge primarily from the chemical, fuels, or forestry industry, and whether a gasification or fermentation route proves more attractive to the UK—and possibly also to other countries. We also suggest that whilst applying system dynamics qualitatively to technological foresight is highly challenging, it can offer a powerful complement to quantitative analysis by highlighting the feedbacks that could be explored and targeted to enable, nurture or reinforce promising developments.

## 7. Nomenclature

RRM	Renewable raw materials
GHG	Greenhouse gas
BTX	Benzene, toluene, xylenes
FT	Fischer–Tropsch synthesis of oil products from synthesis gas

### Causal loops

- + Where a positive sign accompanies the arrow then a change in the variable at the stem of the arrow will lead to a change in the variable at the head in the same direction but not necessarily by the same magnitude

- Where a negative sign accompanies the arrow the opposite is true and an increase in A will lead to a decrease in B, or *vice versa*
- R A complete loop of positive arrows indicates a positive, or reinforcing, feedback which will continue to increase the magnitude of each variable in the loop in the absence of other influences
- B A loop containing an odd number of negative arrows will be balancing, and through a goal-seeking process will try to limit the effects of the increase. Connected reinforcing loops can prevent balancing mechanism from reaching their goal
- # Double lines on an arrow indicate that there is a delay in the transmission of information. This is a key feature that can prevent efficient functioning of management systems through overshooting of targets leading to cycles of profits or actor motivation
- The boxed variable is used to indicate a stock rather than a flow. Stocks are variables that are cumulative and which would remain tangible even if all the information flows were severed, i.e. they can be isolated in time and measured
- Blue text The sections in blue are coloured to depict the variables in the regimes in this study, and those in
- Green text The sections in green show landscape developments that are mainly exogenous to the liquid fuels and organic chemicals regimes.

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